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THE CHEMICAL KINETICS OF THE KATMAI ERUPTION[1]

C. N. FENNER[2]

PART I

ABSTRACT. In papers published several years ago, I gave a description of the pumices ejected in the great eruption of Mount Katmai in 1912. These pumices, in innumerable specimens, show remarkable associations of contrasting felsitic and mafic material, an effect that was ascribed to the assimilation of basic rocks by the new siliceous magma. This view aroused skepticism among geologists as to whether assimilation on such a large scale were credible.

In the present article the possibilities of exothermic reactions in the magma are explored, and the large quantities of heat that may be developed are indicated. This conclusion is based upon well-recognized chemical principles, but whatever might be deduced in this manner, the real basis for conclusions is preeminently the pumices themselves. Therefore, the greater part of the present paper is devoted to detailed descriptions of their field relations, their petrography, and their chemistry, from every relevant standpoint. Most of the evidence presented is new. It points directly and unmistakably to the assimilaton of great quantities of basic rock by the new magma.

The phenomena are different in kind and in magnitude from effects that have been described in other volcanic eruptions. Because of this and because the Katmai region is so difficult of access for study by geologists, descriptions will be given in rather more detail than is usually required.

OCCASIONALLY there appears in discussions among geologists an attitude that seems rather like a protest against the use of physico-chemical arguments to support views of magmatic processes. Probably this attitude is not widespread, and it may be disappearing, but there seem to be definite traces of it still. The implication is that the principles and methods of physical chemistry are so far out of the field of the average geologist that he is unable to judge of their

[1] This work is based largely on studies carried out by the author at the Geophysical Laboratory during his years there as a member of the staff.

[2] Dr. Fenner completed this paper shortly before his death in December, 1949, and arranged to have the manuscript forwarded to Dr. A. Knopf, for reading and submission to this Journal.—*The Editor.*

merits and feels helpless in offering a rebuttal based on purely geological observation. As the present article will use considerable physico-chemical reasoning (of elementary character), it may be desirable as an introduction and preparation for what follows to inquire for a moment into the validity of the protest.

We can probably agree that anyone who applies the principles of physical chemistry to geology should endeavor to interpret results in terms with which geologists are familiar. Above all, everyone should recognize that the conclusions are valid only so far as they agree with geological observations. This is vital. It is in this respect that geologists have had most cause for dissatisfaction. There has been reason to feel that chemists and physicists who have tackled geological problems have not always recognized the value and trustworthiness of the observations of geologists. The blunder of Lord Kelvin in underestimating the age of the Earth, and his insistence that there was no escape from his conclusions, constitute a famous example. In other instances, writers have not intentionally disregarded geological views but have shown themselves unfamiliar with well-established geological relationships. Endeavors to explain all tectonic movements of the Earth's crust by isostatic loading and unloading come to mind.

Now let us look at the other side of the matter.

If geologists are not familiar with the principles of physical chemistry in their application to geology, have they not been remiss in not availing themselves of important tools? Chemists have found these methods of immense value, and modern chemistry is founded upon them. An igneous magma, whatever else it may be, is certainly a chemical solution, to which general laws of physical chemistry apply. It is a very complex solution, differing from anything with which chemists ordinarily have dealt, originating in the depths of the Earth far removed from direct observation and undergoing various chemical and physical changes in its ascent. Anything that offers a logical means of attack to solve its mysteries should be welcomed, provided always that there is no conflict with observations.

Physical chemistry is not a new development, suddenly imposed upon geologists before they have had time to assimilate its principles. Its roots go back more than a hundred years

and are involved in general knowledge of chemistry and physics. Its more direct development may perhaps be associated with the formulation of the law of mass action by Guldberg and Waagé in 1867. This stated in quantitative terms that the advance toward completeness of a chemical reaction is proportional to the concentration of the substances reacting. In 1878 Raoult's important paper on the depression of the freezing points of liquids by the presence of dissolved substances was published. At about this same time Willard Gibbs first enunciated the phase rule, but in a form so clothed with abstruse mathematics that it was not until 1887 that Roozeboom disclosed the fundamental importance of this great generalization.

It was in 1887 also that Svante Arrhenius ascribed electrolytic conductivity to ionic dissociation. Van't Hoff applied this to a determination of the proportionality between the number of ions and the osmotic pressure that they exert, as well as their influence in raising the boiling point and depressing the freezing point of electrolytic solutions.

The principles of thermodynamics, which are the basis of much of physical chemistry, were introduced in their modern form by Clausius in 1850, but it was in the 1880's and 1890's that they were most actively developed in the manner that associated the course of chemical reactions with the quantity of heat evolved and the maximum work obtainable in reversible reactions. Much of this mathematical treatment was essentially the application of the second law of thermodynamics. On this basis quantitative relationships were established and the science of physical chemistry experienced a rapid growth. Many workers, experimental and theoretical, were important contributors, but La Chatelier, van't Hoff, Roozeboom, and van der Waals were outstanding for their multifarious activities.

In the United States, full appreciation of these developments, even among chemists, appears not to have occurred before the late 1890's or early 1900's. Then the teaching of chemistry became revolutionized.

How did geologists react to this new and powerful instrument placed at their disposal? In general, the effect was hardly perceptible for a long time. There were only isolated attempts to incorporate these principles in geologic teaching. As far back as 1861 Bunsen had introduced the idea that a magma is a

solution, and he thus explained that the separation of minerals on cooling is not in the order of their infusibility. In 1892 Barus and Iddings had found that magmas are electric conductors, which leads to the important conception that, to a greater or lesser degree, their constituents are ionized. This and other principles that had been lately developed dealt a heavy blow, not well recognized at the time, to the then-prevalent view that the nature of the compounds existing in a magma could be deduced on the theory of a selective and all-powerful chemical affinity, which decides what combinations take place in the solution and which manifests itself likewise in the minerals crystallizing out. Traces of this idea still survive. Undoubtedly there is a powerful chemical force involved, which may be called affinity, but it is only one of several important factors in determining what combinations shall be formed.

At about this era Vogt and Tammann did very important pioneer work in the application of the newer ideas of geology. Others might be mentioned, but the purpose is merely to raise the question why geologists have not taken advantage of methods of attack made available to them. One might suppose that at this period or a little later the newer chemical ideas would have permeated college atmospheres sufficiently so that students taking advanced training in geology would have become exposed to them by collateral association at least, and would have recognized their value and have taken means to add them to their equipment. Until recently, only a few appear to have thus availed themselves.

In the U. S. Geological Survey the influence of Barus, Becker, and Iddings can be recognized in the establishment, in 1905, of an experimental laboratory. In 1907 this was made the nucleus of a new organization, the Geophysical Laboratory of the Carnegie Institution of Washington.

The importance of the work of the Geophysical Laboratory was recognized almost at once and was hailed with great appreciation, but though its researches have now continued for more than 40 years, the effect upon geological thought has not been quite what might have been hoped for and expected. The importance of its work should have been recognized as lying not only in the experimental results obtained but also in bringing to bear upon geological problems a new method of attack involving a new conception of the properties of magmatic solu-

tions and their products. Petrologists in particular might well have recognized a stimulus to take up a study of the principles of physical chemistry so that this training might become incorporated in their own mental discipline.

The geological interpretation and application of experimental results and of field and microscopic observations in physico-chemical terms should not be regarded as something to be left to a few specialists. The ability to make such interpretations should be part of the equipment of all students of igneous and metamorphic phenomena.

THE LAW OF MASS ACTION

The law of mass action is one of the fundamental tenets of modern chemistry. The law applies primarily to equilibria in homogeneous systems, such as a gas mixture or a liquid solution. With modification it applies to reactions that result in heterogeneous phases, such as the precipitation of a solid or the evolution of a gas from a solution.

Long ago Berthollet observed that the concentration of reactants often determines whether a given reaction or its reverse takes place. In this way may be explained why a chemical change may fail to become complete and may come to a halt before the reactants have been entirely transformed. The forward reaction transforms the reactants A and B into the resultants A^1 and B^1, but is accompanied by a reverse reaction which transforms A^1 and B^1 into A and B. At the halting point each reaction offsets the other. The resulting chemical equilibrium is commonly written $A+B \rightleftharpoons A^1+B^1$.

W. Nernst (1904, p. 432) states: "The genuine kernel of Berthollet's idea is today the guiding principle of the doctrine of affinity. This holds good especially for the conception regarding many reactions that proceed to a completion, *i.e.*, until the reacting substances are all used up; but only for this reason, *viz.*, that one or more of the products of the reaction either crystallize out or evaporate off, and hence the reverse reaction becomes impossible."

Guldberg and Waagé, in 1867, interpreted this condition by assuming that the state of equilibrium attained in a reversible reaction is the result of the speeds of the two opposed reactions, for each of which the velocity V or V^1 can be expressed in terms of a constant multiplied by the *concentrations of the reacting substances.*

Following out the logical consequences of this assumption, they derived a formula for a constant of mass action that expresses these relations in a comparatively simple form.

To represent a reversible chemical reaction we may write the equation $mA+nB \rightleftharpoons m^1A^1+n^1B^1$. Here m mols of A and n mols of B unite to form m^1 mols of A^1 and n^1 mols of B^1. When these substances have reached equilibrium, reactions proceed in either direction. Then, for K (the constant of mass action for any specific set of reactions) we have

$$K=\frac{\text{conc } A^1m^1 \text{ x conc } B^1n^1}{\text{conc Am x conc Bn}}$$

By determining K for any given concentration, the same K is applicable for any other concentration (at the same temperature).

There are two closely related principles on which the law is based. These are the kinetic state of the solution and the reversibility of reactions.

In any fluid, gaseous or liquid, the chemical units—molecular, associated molecular, ionic, etc.—are believed to be in violent agitation, however tranquil the fluid may appear to ordinary observation. Unless viscosity restrains the range of action, they move with great speed in all directions, battering each other and the walls of the vessel in almost infinite collisions. This is simply the classical kinetic theory of matter—the theory that the particles are all in vigorous motion and that this motion is heat, and that absolute temperature is proportional to the average kinetic energy of the particles.

When we apply this conception to chemical solution of several components, a new idea enters. The impact of collisions results in chemical reactions. There is incessant breaking down and regrouping of the chemical units. Obviously, any particular kind of unit undergoes destructive impacts by units of other kinds in proportion to the concentrations of the latter, but its resistance to destruction depends on the strength of the bonds of "chemical affinity" between its atomic constituents. Thus, both concentration of reactants and chemical affinity are factors in determining in which direction reactions proceed. Even at equilibrium there is a constantly active process that brings about an exchange of partners between compounds, a breaking up of molecules into ions, and a union of simple molecules into associated molecules—all the sorts of reactions

that chemistry recognizes. If such a system is isolated from outside influences, the agitation and its accompanying reactions will reach an equilibrium in which it will persist indefinitely. This is a statistical equilibrium and does not imply a cessation of reactions. If the concentration of one of the reactants is increased or diminished, the effect proceeds throughout the system to a new statistical equilibrium.

Many useful applications of the law of mass action have been made by chemists, but in such a complex solution as an igneous magma, in which even the nature of many of the compounds that may be formed is unknown, such a quantitative application is impossible. Nevertheless, important deductions may be made, based simply on the concepts of the law.

We may regard an igneous magma as composed of innumerable combinations of the positive ions Al^{+++}, Fe^{++}, Fe^{+++}, Mg^{++}, Ca^{++}, Ba^{++}, Sr^{++}, Mn^{++}, Na^{+}, K^{+}, and H^{+}, and the negative ions SiO^{-4} S^{-2}, SO_4^{-2}, Cl^{-}, F^{-}, O^{-2}, OH^{-}, and others that are present in minor quantity. Having in mind the evanescent character of some of the products that are likely to result from the thermal battering that they undergo, we realize that combinations and dissociations may occur that are unknown, and probably never will be known, in isolated form.

When a magma is confined in the depths of the Earth the potentially volatile (fugitive) constituents are presumably in homogeneous solution with the other constituents of the melt. From general chemical considerations we may be sure that the volatility that they will later exhibit is not a factor in determining the combinations in which they exist while dissolved in the magma. The combinations that elements form among themselves on escaping are chiefly conditioned by the fact that these specific compounds are able to escape, but in the magma they simply form parts of the mutually reactive ingredients of a homogeneous solution. Chemical affinity and concentration are the primary factors in bringing about a statistical equilibrium, but thermal impacts effect innumerable temporary changes.

There is no reason to assume that in the melt the hydrogen and chlorine, for instance, that are later given off as HCl, are chiefly in this combination, and a similar inference holds with respect to the hydrogen and oxygen or the hydroxyl and

oxygen that are evolved later as H_2O. Moreover, the degree of dissociation in a melt composed of many reactive ingredients has little relation to experimentally determined values of dissociation for HCl or H_2O when either of these is heated by itself. In the same manner, the non-volatile ingredients may be dissociated or may be combined in a way that is not expressed in the crystalline minerals that are finally deposited.

These principles have been well stated by Zies as follows:

"Indeed it seems futile to attempt to trace any volatile constituent contained in the exhalations of an igneous body to some definite compound unless such a compound has already crystallized from the magma. So long as the magma is fluid all we can safely say is that the volatile constituents are dissolved in the fluid and that they will escape if the fluid magma is supersaturated with respect to the new temperature and pressure environment." (1929, p. 43.)

In non-technical language it may be said that hydrogen and chlorine, as an example, have a strong affinity for each other, and, if HCl became broken up by the impacts to which it is subjected in the melt, the hydrogen and chlorine would by preference unite with each other again, but their concentration in a magmatic solution is so small that as a matter of probability they would collide many times with other chemical particles before they would meet the most appropriate partner. Unions of a second or third degree of affinity would be formed. The conception of kinetic equilibrium requires that there should be a certain amount of HCl present, a certain amount of unattached hydrogen and chlorine, and certain amounts of these in other combination. Each of these has definite numerical relations to all the others.

The same picture of conditions in the magma holds for the elements of water and the other volatiles. A hint of the sort of combinations that volatiles form with non-volatiles is given by such minerals as the micas and hornblendes, in which hydroxyl, fluorine, and chlorine occur. Likewise, the amount of water present seems to have an effect on the relative proportions of ferrous and ferric iron. Such minerals crystallizing out represent only a small fraction that has managed to survive of similar combinations that were present in the melt.

We are now prepared to consider what happens when fugitive constituents are given opportunity to escape. As a simple example HCl will again be taken.

It was indicated that among the various combinations that H and Cl could take, equilibrium required that a certain amount of HCl should be present. This would be the principal volatile form in which chlorine could escape, through $FeCl_3$, NaCl, and various others in minor amounts can play a similar role.

On relief of pressure the HCl present as such begins to come out of solution in the hot magma and depart as bubbles of gas. This removes from the system one of the constituents on which the whole statistical equilibrium in the solution depended. Reactions are at once set in motion by which an attempt is made to replace the HCl, but, as soon as it is newly formed, it is free to escape. The same idea is applicable to all the other constituents that are capable of forming volatile compounds. It is easy to see that the equilibrium of the whole system is destroyed and the utmost chemical confusion results. In such a state of affairs evanescent combinations are formed which are not in equilibrium with anything.

Suggestions of similar import have been made by other geologists, but usually in a form that emphasizes reactions among unstable associations of gases that might react with each other *after* they leave the magma. These reactions may be very important, but I would emphasize the reactions within the magma itself that lead to the evolution of gases.

In these events each individual reaction between the infinitesimal units is accompanied by a minute heat effect, positive or negative, but the system as a whole is so immensely complicated, and there is so little information in the reactions of separate constituents that no calculation of the net heat effect is possible. The evolution of heat might be very great. If, for instance, combination of hydrogen and oxygen or of hydrogen and hydroxyl to form water were a chief reaction, this would be highly exothermic. Or, on the other hand, the net effect in the system as a whole might be negative. Consideration of certain features not yet discussed will help in deciding which it will be. The value of having such a picture in mind is that it is a guide in directing us to what should be looked for.

At this point it is necessary to recognize that even the general picture given so far has not been made general enough, and that by use of similar conceptions of the conditions within a magma, a somewhat different process might be formulated.

Let us suppose that a silicate mixture plus water is heated in an impervious container until a homogeneous melt is produced. A certain equilibrium is established. Now let us cool the melt until crystals form. The water in the melt thereby becomes concentrated, bubbles are developed, and the vapor pressure over the melt is increased. With further cooling and increasing crystallization the vapor pressure may become very great. A *retrograde* boiling is thus effected by *cooling*. If cooling and consequent crystallization are fairly rapid, the melt may froth up into a pumice.

The significant difference between the first process pictured and the second is that in the first the relief of pressure allowed the volatiles to escape and thereby upset the equilibrium, with possible evolution of heat. In the second process, crystallization upon *cooling* is the important factor. The second process, in its nature, excludes the possibility of the melt becoming hotter; the first recognizes that internal reactions may be exothermic, thereby giving to a magma the power to assimilate xenoliths.

The second process is that which Morey has favored to explain important magmatic phenomena, such as increasing vapor pressure and consequent explosions, formation of pumice, and migration of volatiles into wall rocks. He takes as an illustration the experimental system H_2O—K_2SiO_3—SiO_2, and shows the rapid increase of vapor pressure that results from the crystallization of quartz and the compound $KHSi_2O_5$, and applies the results to magmas as follows (Morey, 1922, p. 226):

"As a magma containing water and other volatile components cools, with consequent crystallization, the pressure will rapidly rise from its initial value, and, as the cooling continues, the pressure will increase until the temperature of maximum pressure has been reached, or until the pressure is relieved by the escape of the volatile material."

He believes that this system can fairly be taken as analogous to natural magmas. Morey explains pumiceous explosions in volcanoes in this manner, and many geologists have accepted his explanation as the chief cause of such effects.

The applicability of Morey's results in this manner seems to require more evidence. Each system has its own characteristics, and the course and speed of reactions in this alkalic system may be quite different from those in natural magmas. The chief reason for dissent, however, will appear in later

sections of this article, where a step-by-step analysis of what occurred in the Katmai eruption will be given. Morey's process calls for cooling and confinement of the magma while pressure is built up. I hope to show that in the Katmai eruption the explosions occurred after the magma rose to the surface and was lying in an open crater, and that during this period a great amount of heat was evolved and large quantities of cold rock from the crater walls were engulfed by the magma and reacted with it. The later explosions developed in the syntectic magma so produced.

We may quote here as relevant a statement by Nernst (1904, p. 675). Under the heading "Temperature and the reaction velocity," Nernst sets forth a general principle: "Let us . . . consider the case where the reaction progresses in the sense which is associated with the *development of heat* (Nernst's italics). As a result of the progress of the reaction, there ensues an elevation of temperature, which in turn accelerates the velocity. But this accelerated velocity . . . . occasions an increased development of heat, which again reacts to hasten the decomposition. Thus it is evident how a very extraordinary acceleration of the reaction velocity may take place under favorable circumstances. In this way we can explain the "stormy reactions." *It will be found invariably that these are associated with a development of heat*" (my italics).

This principle is the basis of the following discussion by von Wolff (1919, p. 119), applied directly to volcanism:

"Lowering of temperature, and, still more, removal of pressure are closely connecting with the uprising and extrusion of the magma.

"We shall have to distinguish between two cases:

"1. The change of temperature and pressure proceeds very gradually. In that case the chemical systems have time to adjust themselves to the changed exterior conditions through the bringing about of new equilibria. The condition of equilibrium is maintained. Eruptions that proceed in a non-violent manner, like that of Kilauea, may approach such conditions.

"2. The change of temperature and the unloading occur so quickly that time is not sufficient for the attainment of new equilibria. The chemical systems thereby attain an unstable condition . . . . Reactions set in with the goal of reaching the new equilibrium. In this case the velocity of reaction attains a

great significance. *Reactions which . . . proceed exothermally . . . experience through the heat thereby generated a continually increasing acceleration of reaction, which finally leads to explosion.* Through the same processes the gases dissolved in the magma are set free . . . . The setting-free of gas is an accompanying phenomenon of the uprise of magma, not its cause" (my italics).

The conception of exothermic "stormy reactions" set forth here by two eminent authorities is a fundamental principle of utmost importance, which should have been of common knowledge for 50 years. Why have geologists in general not recognized it and applied it? Instead they have repeated many times Harker's obfuscating argument against assimilation and hybridization: "The insuperable objection to any such theory is that it demands an enormous amount of heat to raise the solid rocks to the point of melting and to melt them, and no source for this heat is indicated" (1909, p. 339).

Detailed evidence will be presented that a large amount of assimilation did take place in the Katmai magma and that the supply of heat that Harker declared to be non-existent is to be found in the reactions discussed in earlier pages.

In dissenting from Morey's conclusions I would not argue against the principle that crystallization does increase the vapor pressure of the fugitive constituents in a confined system, or deny that in some circumstances it is very important in magmas. Increase of vapor pressure in a confined solution containing volatiles, on cooling and crystallization, is inevitable. One consequence is that it is impossible to ascertain the original volatile content of magmas by studying cold rocks. What I wish to express is serious doubt that Morey's process is competent to explain the phenomena of the Katmai eruption and similar explosive outbursts. Every feature of the Katmai eruption is opposed to it.

THE STRUCTURE OF MOUNT KATMAI

A geologist coming into the Katmai country in the years following the eruption found himself faced with phenomena for which no text-book descriptions, or even experience in volcanic regions that had been less recently and less violently active, would have prepared him. He would be surrounded by factual evidence of volcanic processes for which text-books either gave no explanation or gave explanations obviously out of accord with what he saw.

Explosive eruptions of the magnitude of that of Mount Katmai are exceedingly rare, and the few that have occurred in recent times have been in regions not easily accessible. The products of pumiceous eruptions are easily removed by streams or winds. Ordinarily the ejects have been deposited on contiguous mountainous areas, where erosion is especially rapid, and within a short period some of the most significant evidence of their original relations are likely to have been destroyed or obscured. It was our good fortune to be able to study this uniquely significant region while the evidence was still clear and undisturbed. For this our thanks are due to the Geophysical Laboratory of the Carnegie Institution of Washington and the National Geographic Society. My second visit to the region was greatly facilitated by the U. S. Geological Survey.

Major problems to which the members of the Geophysical Laboratory staff—Allen, Zies, and Fenner—gave their attention were the following: What was the nature and origin of the great tuff deposit in the Valley of Ten Thousand Smokes? The only previously described deposits that resembled it were those of the West Indian *nuées ardentes* of 1902, and in some respects these were so different that the fundamental similarities were not immediately apparent. What was the composition of the fumarolic gases evolved and the minerals deposited by the fumaroles? What was the explanation of the strangely variegated assortment of pumices erupted? Specimens of white, black, gray, red, brown, and banded pumices in thousands or tens of thousands were visible everywhere. They impressed everyone coming into the region, until by familiarity with their enormous numbers they became commonplace. They were obviously a mixture of felsitic and mafic constituents and for a geologist they were a problem that demanded attention and explanation. How did a mixture of these ingredients in closest association originate? In the main crater of Katmai and the parasitic crater of Novarupta highly explosive magmas had lain quiescent at times and then had detonated with stupendous violence. What internal reactions was the magma undergoing in the quiescent periods? What became of the material that disappeared from the former peaks of Mount Katmai, leaving a great crater pit? Contributions toward the solution of these problems have been published in various articles (Griggs, 1922; Allen and Zies, 1923; Zies, 1929; Fenner, 1920, 1923, 1925, 1926, 1930, 1933, 1934, 1937, 1938, 1944, 1948). In the

present article a large amount of hitherto unpublished data and conclusions as to their bearing will be presented. In order to work these into a coherent picture, it will be necessary to repeat small parts of previous description.

A chart (No. 8555) of the U. S. Coast and Geodetic Survey shows that prior to the eruption Mount Katmai was composed of three peaks, of which the most southerly was 7500 feet (2287 meters) high and the others were 7360 feet and 7260 feet respectively. When the eruption was over only a hollow stump of the mountain was left. (For illustrations see Griggs, 1922, pp. 101, 173, 177, 179; Fenner, 1926, p. 687; 1930, plates II-IX.) The peaks had vanished, and an enormous pit had been formed. Surveys made by the National Geographic Society Expedition show that this abyss is 2.6 miles (4.2 km.) in greatest length and 4.2 square miles in area at the rim. The highest point on the rim (northerly side) has an elevation of 7000 feet (2135 meters) and stands 3700 feet (1128 meters) above the floor of the crater (Griggs, 1922, p. 177). Sags in the rim on the southeastern and northwestern sides have elevations of about 5100 feet (1555 meters). These are remnants of troughs of glaciers that came down from the upper slopes and were beheaded by the eruption.

In the first years after the discovery the floor of the pit was covered by a lake, from which rose a horseshoe-shaped island. This was the condition in which I saw it in 1919 from the southeastern rim, but in an ascent of the mountain on the northwestern side, in 1923, I found that the lake had disappeared except for a lagoon inclosed by the island. A descent from the northwestern rim to the floor, down a narrow trough, was found possible, and I was enabled to examine the crater at close range. In a number of places on the floor there were boiling springs, and a large mud geyser erupted at frequent intervals (Fenner, 1930, plates II-IX). The floor, in general, was nearly flat, and the former lake had evidently been shallow. The horseshoe island was composed of andesite, platy or ropy. It was believed to have been a final non-explosive extension of lava from the main vent. The lagoon enclosed by the crescent appeared deep.

In the view of the crater in 1919 I had noted that great heaps of debris had slumped from the walls on the northern and southern sides. In 1923 these heaps appeared little changed.

They were estimated to be 500 to 800 feet (150 to 259 meters) high. Similar slumping is believed to have occurred during the eruption, and the masses of rock were submerged in the cauldron of fresh lava and were rapidly attacked.

The character of the walls of the crater is important, but their study from the floor was not altogether satisfactory, for they had been washed over by muddy streams from the rim. It was plain, however, that they were not composed altogether of lavas. On the west side especially, sedimentary strata were discernible. Other parts of the crater wall around the circumference suggested sediments rather than lavas. The most definitely igneous rocks were on the eastern side, where dark red and nearly black masses formed the walls. In the glacial trough at the rim, seen in 1919, were boulders of mafic lavas which had been carried down from the former peaks, and the adjacent rocks in place were lavas.

On the crater floor rock fragments were of considerable variety. Effusive lavas, purple, red, and black, probably predominated, but there was much shale, some of it having a "baked" look. A large boulder of sandstone was prominent. The lavas varied from aphanitic to porphyritic.

In the descent into the crater from the northwestern rim most of the slide rock under foot was sedimentary, generally a hard shale.

The rocks on the outer slopes of the mountain confirm and supplement these observations. On the southeastern rim are lavas only, and lavas cover most of the southern and southeastern side of the mountain. They descend in fairly smooth slopes until they break off abruptly at the canyon of Katmai River (fig. 1). At the bottom of Katmai canyon shales and sandstones crop out under andesites and basalts that rise 1400 feet (425 meters), in steep cliffs. The sandstone surface that passes under the lava has been planed off and scored by unmistakable glacial action over a wide surface. All the lava flows have a topographically youthful appearance and the volcanicity of the mountain may be very young. In contrast, the neighboring Mount Trident has been much more dissected.

The western side of Mount Katmai and the continuation of the range northwesterly are of irregular relief, and even from distant views many peaks are evidently composed of horizontal sediments (Fenner, 1930, plate II). In the course of our ascent

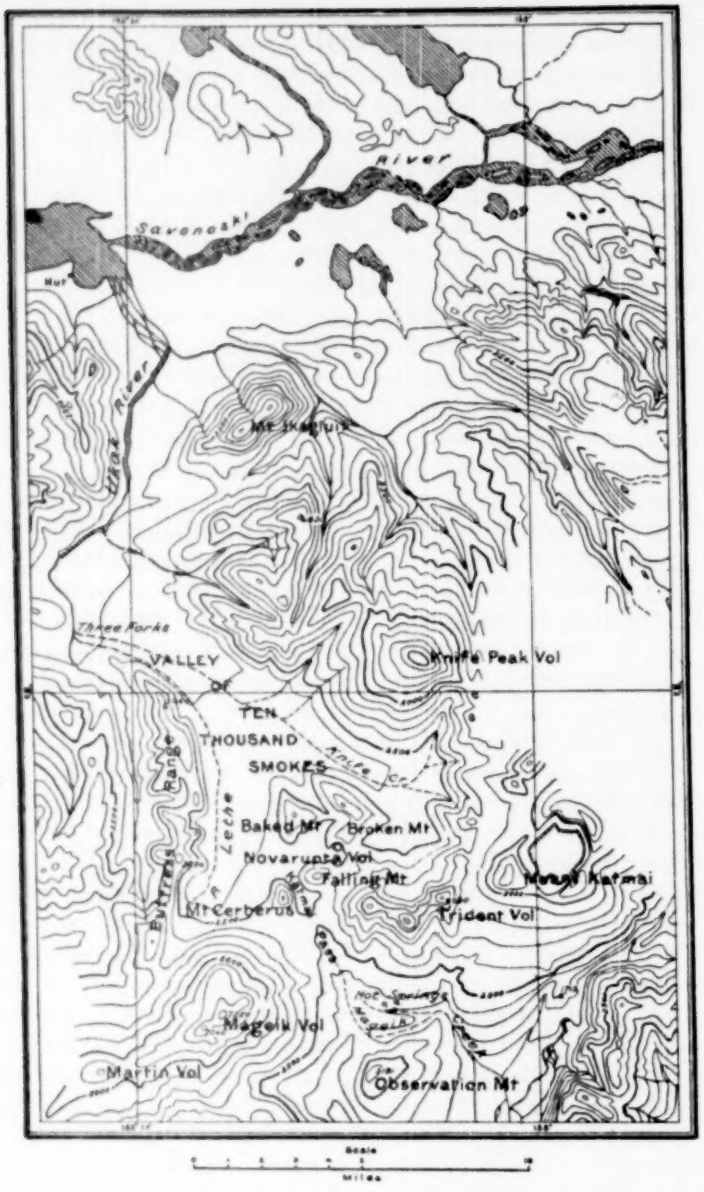


Fig. 1. Map of the Katmai region, from surveys of the National Geographic Society and United States Geological Survey.

on the northwestern side sedimentary rocks were seen to form all the adjacent exposures until we were up near the rim of the crater, where very dark igneous rocks rose in masses.

The sediments in the Katmai region include beds of limestone, and the shales are fossiliferous.

The conclusion regarding the inner walls of the crater pit is that both lavas and sedimentary rocks are present, perhaps in nearly equal amount. The high peak on the northern side is apparently sedimentary, but in most places the sedimentary rocks rose no higher than the present northwestern rim, and on the southeastern side were lacking. The high peak in which the original crater lay was presumably igneous. We shall look for evidence of these wall rocks in the contaminated ejectamenta.

In the Katmai region the most abundant lavas by far that have been poured out by the five volcanoes Katmai, Mageik, Trident, Knife Peak, and Martin are medium to basic andesites and basalts. Many are porphyritic, often with a fine-grained or aphanitic groundmass. The phenocrysts are plagioclase, augite, hypersthene, and magnetite, generally in glomeroporphyritic groups. We should expect to find evidence of these characteristics in the contaminated lavas. Specimens of granitoid rocks are practically absent among the eruptive products. I found not more than half a dozen small specimens in the region. The shattering explosions of the eruption did not reach to great depth. The new magma, as it rose from the depths, was a very siliceous rhyolite, but, as will be shown, it became greatly contaminated by the assimilation of these basic wall rocks.

FEATURES OF THE ERUPTION

The state of the volatiles in a magma, according to the conception given in the preceding pages, must have important consequences on the mechanism of eruption. When relief of pressure gives opportunity for volatiles to escape, they may not be able to take advantage of it immediately. Relief of pressure favors the escape of gases, and therefore reactions proceed in the direction that leads to the formation of gases, but the rearrangements may require time for their development. In a chain of chemical reactions a bottle-neck may occur which slows down the whole series (according to Guldberg and Waagé's conception of variable reaction velocities); but, as we have seen in the quoted statement by Nernst, the speed of

reactions increases rapidly with rise of temperature, and, if the net effect in a magma is exothermic, reactions that have begun very slowly proceed more and more rapidly, at a high compound interest rate, as the temperature rises, and finally reach a cataclysmic stage.

This conception is believed to explain important features of the Katmai eruption. As will be shown, potentially explosive magma that had risen to the surface in the crater remained at times relatively quiescent while it assimilated large quantities of wall rock that had been broken off in masses by the explosions. Possibly corrosive attack upon the walls had weakened or undermined them; at least there was rapid disintegration and assimilation of the submerged blocks. Then the contaminated magma became inflated with great violence because of the sudden setting-free of gases throughout its mass.

In volcanological descriptions we often find statements or implications to the effect that magmas heavily charged with fugitive constituents explode immediately when physical constraints are removed, but, if we read the accounts carefully, we see that in many eruptions that does not agree with the records themselves. The phenomena at Katmai show factors other than physical restraint are extremely important.

The relative duration of the quiescent and explosive periods at Katmai is somewhat uncertain because of lack of direct observations. The nearest of the few native inhabitants of the region were at Katmai Bay and at Naknek Lake, and, wisely, they left before the more violent manifestations developed. Information that bears on the matter is contained in reports gathered by Griggs at distant points (Griggs, 1922, pp. 7-31). A bare digest of the most important is as follows: June 6, 1912, morning: Frequent minor explosions and earthquakes noted at Seldovia (144 miles N.E.) and Nushagak (131 miles W.N.W.). These were probably due to (or accompanied) the outburst of the incandescent tuff-flow in the Valley of Ten Thousand Smokes. June 6, 13 hr.: Terrific explosion and earthquake noted at Cold Bay (40 miles S.W.); smoke cloud seen by captain of steamer "Dora" entering Kupreanof Straits (to the S.E.) and bearings showed that it came from Mount Katmai. "The smoke rose and spread in the sky, following the vessel, and by 3 P.M. was directly over us, having traveled at the rate of 20 miles an hour." This was probably the beginning of the

violent phase of the eruption in Katmai crater, continuing sporadically until June 8. June 6, 15 hr.: Second tremendous explosion heard for hundreds of miles around. June 6, 23 hr.: Severe earthquake at Cold Bay (40 miles S.W.), and a strong glare of light seen from Kanatak (59 miles S.W.). June 6: During the night, a number of severe earthquakes at Kodiak (100 miles E.S.E.). June 7: Earthquakes all day at Kanatak (59 miles S. W.). June 7, 23 hr.: Strong earthquake, with heavy rumbling, rock slides, and glare of light at Kanatak (59 miles S.W.). After midnight, a noise like heavy thunder from the direction of Katmai. June 8-9: Various effects indicate eruption continuing with lessened violence. For the remainder of June and all of July, reports of ashfall and earthquakes from various points.

These reports indicate that the violent explosions took place on June 6 to 8. The periods of comparative rest seem to have lasted longer than the violent phases; in fact, the explosions appear to have been of short duration. The studies of ashfall (see later) confirm the alternations of major explosions with quiet intervals. It is believed that in the quiet periods the assimilation of large quantities of wall rock by the new magma occurred. The submergence of masses of cold rock in the magma probably lengthened the periods of quiet, but it was not the whole cause of the delay, for uncontaminated (or nearly uncontaminated) magma underwent at times a similar pause and subsequent inflation.

The contrast between the dark mafic rock of the walls and the white rhyolite preserved a record of processes at work, which helps greatly in the interpretation of the nature and sequence of events. If the assimilated rock had been of felsitic or even of intermediate composition, it is doubtful if satisfactory evidence of assimilation could have been established, and it might have been completely overlooked.

There are corroborative evidences of open pools of explosive magma standing for a while in the crater before bursting forth. The most common product of the eruption was highly inflated pumice, but a material that I have called "volcanic scum" was found everywhere within the area of coarse ejecta. It occurred as angular blocks, rather flat, three or four inches (7.5 to 10 cm.) thick. These blocks are interpreted as fragments of a crust that congealed at times at the edges of the pool. Many

specimens were collected, and supplied interesting information. In a matrix of glass which was intrinsically dark but so filled with tiny bubbles that it appeared gray, was a heterogeneous collection of xenoliths and xenocrysts—angular pieces of old lavas, sediments, obsidian, pieces of scum from previous explosions, pumices and separate crystals—collectively representing the sort of scum that might be expected on the surface of the miscellaneous stew that the magma had become. The fragments of pumice included in this scum appear to have been somewhat softened by re-immersion and have lost their highly inflated character but are still very vesicular and are easily identified. Some have retained their angular form, but others have been drawn out into bands.

We should naturally expect that pumice which had been ejected and had fallen back would float on the surface of the lava, but accompanying it in the blocks of scum is rock of much greater density. This must have been carried to the surface by rising currents in a seething pool, and the whole conglomeration swept to one side, into a cooler situation where it congealed.

Examination with a binocular magnifier shows that narrow tongues or irregular apophyses of glass penetrate the xenolithic inclusions of the blocks. Thin sections of the "scum," studied microscopically, reveal clearly what was happening to xenoliths. Feldspar phenocrysts are riddled with brown glass, especially in certain of the oscillatory zones, and pyroxenes are attacked and penetrated by glass.

If phenocrysts weakened in this manner had not been held in a rigid glass during subsequent explosions, they would generally have been torn apart, and the distinct evidence of attack would have been destroyed. Occasionally specimens from the stratified ashfall show an intermediate stage. Parts of phenocrysts that were originally single units, but are now slightly separated, have their fractured surfaces attached to each other by threads of glass.

A substance related to the "scum" is a very dark (nearly black) glass with or without inclusions. This also probably formed a crust at the edges of the lava pool. When heated over a Bunsen burner it froths up into pumice. Evidently it retained some of its volatiles during congelation.

The high mobility of the magma is shown by its ability to

penetrate xenoliths. Among the ejecta of Mount Katmai and Novarupta are many specimens of scoria and pumice so dark-colored and basic that they are believed to represent blocks of basic lavas which were submerged in the liquid magma and became softened clots, but had not yet mingled freely with the liquid. Nevertheless many are much inflated. It is thought that the rhyolite liquid was so highly mobile that it soaked into these xenoliths and permeated and softened them so thoroughly that they became inflated at the same time as the liquid magma. Specimens of this sort are more common in the ejecta of Novarupta than of Katmai. Though they are fairly common in the ejecta of Katmai, on the whole, assimilation in the crater of Katmai progressed further and more nearly homogeneous products resulted.

The view that rhyolitic magmas are essentially highly viscous seems to persist in spite of much evidence to the contrary. When they have lost their volatiles and have been somewhat cooled, they are viscous as warm tar, but, in their pristine condition, they flow freely and soak into xenoliths without difficulty. Among the great rhyolite flows in Yellowstone Park all degrees of viscosity may be observed.

THE STRATIFIED KATMAI ASHFALL[1]

During the eruption of Mount Katmai a large quantity of ash was carried by the wind to the town of Kodiak, 100 miles (161 km.) distant to the east-southeast. In 1919 a measured section was found to be 10 in. (25 cm.) thick, after seven years of settling and packing. The wind direction during the eruption was toward Kodiak, but five hours was required from the beginning of the first violent phase of the eruption, as observed by the captain of the steamer "Dora" in Kupreanof Strait, to carry the ash 100 miles. Therefore the wind was not violent. That the ash took so long to settle means that it was thrown to a great height. This ash was not an impalpable dust. The bottom layer consisted of 4½ in. (11½ cm.) of light-gray

[1] The term "ashfall" will be used for the accumulations of ejecta from Katmai and Novarupta that had been thrown violently into the air and had settled over the surrounding country. Most of it was pumice, but it contained small amounts of some un-ashlike materials. It is to be distinguished from the incandescent tuff-flow (abbreviated in places here to "incandescent tuff") that was ejected with less violence and flowed over the surface of the ground.

sand; the second measured 4 in., light-brown sand at bottom, very fine sand at top; and the top layer was 1½ in. of light-gray, fine sand. Most of the material was glass of index 1.480, but it contained calcic feldspars and rare fragments of pyroxene. The five hours of travel had made only a partial winnowing of heavy material from light.

In the opposite direction from Mount Katmai, that is, to the northwest, and about 21 miles (34 km.) from Katmai, a section of ashfall at one camp on Naknek Lake (northwest corner of map) measured 10½ in. (26.6 cm.) in depth. There was not much differentiation of layers by size of particles except for one coarse layer. The same minerals were present as at Kodiak.

Much thicker layers of undisturbed Katmai ejecta are present near the mountain, on the south and southwest, in the valley of Katmai River. Recent stream-cutting had exposed sections well situated for close examination and sampling. Study of these on the ground and petrographic and chemical investigation in the laboratory gave much important information on what processes were at work in the course of the eruption.

Three sections of Katmai ashfall on the western side of the valley of Katmai River were measured and studied in 1919 and two others in 1923. The first was at our Camp IV (near southeast corner of map, a little north of point where Mageik Creek leaves the map). The other two sections of 1919 were at points farther south, and the two of 1923 farther north. The thickness of the deposits lessened quite rapidly in going south from Camp IV and increased in going north. In all the sections, corresponding layers were very similar.

The deposit at Camp IV and one of those studied in 1923 will be described as typical. The description of the layers will follow the order of deposition: A-175 is the bottom layer.

KATMAI ASHFALL AT CAMP IV

The lowermost layer rests on old turf.

A-175. 18 in. (45.7 cm.) of coarse pumice. Largest pieces (omitting exceptional ones) are 3 to 4 in. (8 to 10 cm.) long. The pumice is pure white, but it is mixed with stony lapilli. There is very little difference in size of pumice lumps from bottom to near the top; then a rapid change takes place and

the top 1 in. is of pea size or less as an ordinary maximum, with most pieces much less. There is almost no very fine material to fill interstices. A large part of the lapilli is black and red, stony (not glassy) andesite, but there is also burnt-looking shale. The quantity of lapilli is hardly sufficient to suggest that they represent the blasting-out of an old plug in the conduit, but rather that there had been some accumulation of loose rock. Neither is there in the composition of A-175 any evidence that it had to melt out a plug of old lava before it could rise into the crater. The pumice of this first layer is purest rhyolite (see analyses, table 1). No streaked or variegated (black-and-white) pumice was observed.

A-176. 3½ in. (9 cm.) terra-cotta layer, of hickory-nut size (3-4 cm.) at bottom, decreasing rapidly and progressively to very fine (sandy) material mixed with some coarse at top. The lumps of pumice are generally white, but there are dark pieces and black-and-white streaked pumices, evidence that assimilation of basic rock had begun (see table 3 and diagram of analyses). The terra-cotta color seems to be due entirely to a coating of fine mud.

A-177. 11 in. (28 cm.) buff layer. Coarse pumice, up to maximum of 2-3 in., with very little fines. Contains white, gray, red, striped and nearly black pumices, stony andesites, burnt shale, and dense glasses, both dark and variegated. Assimilation had greatly increased, but products have not been uniformly mixed.

A-178. 2 in. (5 cm.) yellow layer. Essentially the same as last, except that many pieces of pumice are stained a bright orange color—evidently volatile iron compound had been evolved. The lumps in this layer are somewhat smaller than in layer below and A-178 might be considered the top portion of A-177. In A-179 the size increases again.

A-179. 9 in. (23 cm.) buff layer. Made up largely of buff or reddish-brown pumice, coarse. Not so much very dark pumice as in A-177 and A-178. Contains fragments of stony andesite, burnt shale, and dense glasses, both dark and variegated. Pumice has become more uniformly basic. Assimilation and mixing are far advanced. The top of A-179 is less coarse than lower portion, and is succeeded by coarser in A-180.

A-180. 50 in. (127 cm.) gray layer. Major outburst. Very coarse at bottom and for most of its thickness, with lumps up

TABLE 1

Analyses of pumices of the eruption. Nos. A-175 to A-187 are successive layers of ashfall. Column of combined analyses gives calculated composition of average pumice.
A-505 is pumice from a second section corresponding in position of A-181 of first section.
A-547 is andesite of horseshoe island in Katmai crater.
A-185X is white pumice selected from basic sample A-185.

	A-175	A-176	A-177	A-178	A-179	A-180	A-181	A-182	A-183	A-185	A-186	A-187	Combined analyses	A-505	A-547	A-185X
SiO_2	76.53	75.56	71.92	69.37	64.61	65.98	68.00	67.43	60.85	57.99	63.56	64.36	69.14	67.48	65.90	75.08
Al_2O_3	12.31	12.10	13.30	14.28	15.40	14.93	14.58	14.52*	16.28*	17.39	15.72*	15.81	14.34	14.51	15.89	12.13*
Fe_2O_3	.46	.77	.81	1.44	1.97	1.91	1.66	0.92	2.70	2.76	2.73	2.75	4.41	1.46	1.61	2.25
FeO	.96	1.06	1.97	2.54	3.50	3.11	2.75	2.95	4.68	4.75	3.67	2.50		2.99	2.70	
MgO	.00	.59	1.11	1.66	2.24	2.07	1.65	1.53	3.17	3.42	2.48	1.99	1.68	1.66	1.90	.82
CaO	1.01	1.54	2.88	3.77	5.23	4.95	4.07	4.08	6.06	7.49	5.39	4.29	3.88	4.02	4.55	1.55
Na_2O	4.15	4.09	3.99	3.78	3.78	3.87	3.92	3.88	3.84	4.03	4.00	3.62	3.95	3.88	4.11	
K_2O	3.05	3.00	2.53	2.18	1.77	1.74	1.98	2.16	1.35	1.06	1.62	1.56	2.12	2.20	1.69	
H_2O+	.87	.73	.67	.56	.37	.37	.42	0.67	.48	.36	.54	1.33	....	.47	.42	
H_2O-	.25	.22	.16	.13	.16	.11	.13			.07		.73	....	.15		
TiO_2	.17	.19	.33	.47	.65	.59	.53	0.55	.94	.81	.72	.59	0.48	.52	.62	.27
MnO	.04	.05	.07	.09	.09	.09	.07	n. d.	n. d.	.15	n. d.	.10	....	.09	n. d.	
BaO	.07	.07	.07	.08	.07	.06	.05	n. d.	n. d.	.05	n. d.	n. d.	....	.06	.05	
P_2O_5	.05	.01	.08	.16	.19	.13	.14	n. d.	n. d.	.22	n. d.	.15	....	.26	.17	
Cl	.23	.20	.17	.14	.15	.13	.13	n. d.	n. d.	.07	n. d.	.09	....	.14	n. d.	
S	.01	.01	.03	.03	.03	.04	.02	n. d.	n. d.	.07	n. d.	.17	....	.08	.25	
	100.16	100.19	100.09	100.68	100.21	100.08	100.10	98.35	100.35	100.69	100.43	100.04	100.00	99.97	99.86	

*Incl. P_2O_5

to 2 or 3 in. (5¼-8 cm.). Top 20 in. (50.5 cm.) considerably finer, with maximum of pea size. In this top 20 in. there is a minor stratification due to alternations of size, grading into each other. In A-180 as a whole there is very little really fine material. Pumice predominates over dark lapilli much more than in lower layers. The general color effect is uniformly gray, but white, light-gray, buff, and terra-cotta varieties are present. There is little or no very dark pumice. Assimilation and mixing have well advanced toward homogeneity. The top of A-180 is separated sharply from A-181.

A-181. 8 in. (20½ cm.) light-gray layer. In lower 5 in. the pumice is coarse, with many lumps 2 in. (5 cm.) in length. Then it changes quite rapidly to a grit or coarse sand at top. Is composed mostly of white pumice, but there is a little gray and terra-cotta pumice and dark lapilli. The large amount of white pumice shows that there had been an important new upsurge of rhyolite magma, and that this had not mixed thoroughly with the contaminated lava when inflation occurred. Very likely there was a fairly continuous upwelling of fresh rhyolite into the crater all through the eruption, for none of the principal layers of the ashfall is homogeneous—all contain some white pumice—but in A-181 the amount becomes large. A-181 is separated sharply at top from A-182.

A-182 8 mm. fine sand, light-gray.
A-183 10 mm. light-gray grit or coarse sand.
A-184 6 mm. fine sand, light-gray.
A-185 36 mm. light-gray grit.
A-186 28 mm. light-gray sand.
A-187 35 mm. dark reddish-brown sand below, purple sand above.

Layers A-182 to A-187 are sharply separated from each other.

A thin deposit of purple or lavender sand or mud (A-187) is generally present on top of the ashfall over a wide area.

Noteworthy is the evidence of repeated dying-down and renewal of explosive activity, shown by the decreasing size of the ejecta toward the top of each important layer, the sharp break between layers, and the increased size of pumice deposited at the succeeding outburst. Inflation and ejection of the magma, when once begun, was not a process that continued until all the potentially explosive magma on hand was exhausted; in-

stead, the inflation reached to a certain depth of magma in the crater and then halted for a while until internal reactions had set free the latent explosivity of another portion. The portion of magma that exploded at any one outburst was that from which volatiles had been free to escape into the atmosphere, thus setting off the chain of internal reactions that developed the latent explosivity and culminated in the outburst.

Further description of the pumices and their minerals will be given in the petrographic section.

Perret, who contributed greatly to volcanological knowledge by years of study, at close range, of eruptions in actual progress, has described similar delayed explosions witnessed during the eruption of Mount Pelée in 1929-1932:

"Certain conditions displayed in the present eruption had been hitherto unknown at Pelée; among them the presence of liquid lava in pockets and vents, open to the atmosphere, where the well-known crater glow persisted for days at a time. From these craters occasionally burst forth nuées ardentes." (Perret, 1935, p. 86). He considered it somewhat remarkable that at Katmai it had been possible to deduce this phenomenon without its having been witnessed. Actually, the evidence at Katmai was so clear that it could hardly be missed.

SECOND SECTION ASHFALL IN KATMAI VALLEY

The next section of ashfall to be described was at a point four or five miles north of the first section and about four miles due south of Katmai crater. Plate 1 is a photograph of this deposit. This section was studied with special care in 1923, as a check and confirmation of the studies of 1919, after the material collected then had been worked over petrographically and chemically in the laboratory.

This second section was as follows:

At bottom, boulders, overlain by a fibrous mat of dead turf, roots and twigs.

A. 48 in. (122 cm.) Pure white pumice, mixed with lapilli of basic to medium lavas and sediments. The igneous rocks are reddish-brown, purple, gray, and black, and are generally porphyritic. They have the appearance of the lavas seen in place in various localities around Katmai. (Note later, in the petrographic section, how the character of these lapilli agrees with the character of fragments in the succeeding layers of

pumice that have been attacked and are in process of solution.) The sedimentary lapilli are both shale and sandstone, the former preponderant. Many are blackened, some reddened. The lapilli occur throughout layer A. Are more plentiful in bottom 18 in. (46 cm.), but are mixed with pumices there as throughout the layer. Are mostly in small bits but occasionally reach 2 in. in diameter. Are of angular shapes. Sedimentary rocks exceed igneous lapilli. An estimate of foreign lapilli in lowest 18 in. of A was 15 to 20 per cent by volume. This amount of *unassimilated* xenoliths is much greater than in succeeding layers. The pumices are all in angular pieces, with no rounding even of edges. Most of them are firm but an occasional piece is very frothy. Ordinary maximum size is 2 to 3 in. (5 to 8 cm.), but pieces of 5 in. occur. All the pumice is pure white, except that two light-gray or faintly banded pieces that contained a few dark phenocrysts were found after close scrutiny of many lumps. A small amount of pumice is superficially stained yellow. No phenocrysts of quartz or feldspar are visible (*i.e.*, in the examination in the field). The interstices among lumps are filled loosely with fines. In top 1½ to 2 in. of this layer few pieces are larger than pea size.

B. 1½ in. (4 cm.) buff layer. The lumps of pumice are still perfectly white and without phenocrysts, but buff-colored mud coats the pumices and partly fills the interstices. The lumps are ½ in. in diameter as an ordinary maximum. Shale and andesite are present. B is very much like A except for the buff mud, but this makes the layer distinct.

C. 16 in. (41 cm.) light-gray or buff. Most of the pumice is white, with very sparse dark phenocrysts (xenocrysts), but there is a considerable amount of brown and gray pumice with phenocrysts, also variegated (striped) pieces. Sedimentary fragments and igneous lapilli are less than before. Lumps of pumice are angular. In most of C the ordinary maximum is 1½ in. (4 cm.), but in upper 1½ in. there are more fines. A minor horizontal banding of layer is visible. The notable feature of C is the sudden appearance of a considerable quantity of dark and variegated pumices with xenocrysts. The striping of the pumices is distinct and unmistakable. (Assimilation has advanced, but homogeneity has not been attained.)

D. 5 in. (13 cm.) yellow or orange layer. White pumice without phenocrysts is still present, but most is brown, gray,

pink, or yellow, with dark phenocrysts. The first appearance of volcanic conglomerate ("scum") is noted in D, and the pieces are numerous. The yellow color that distinguishes D is probably a stain but is very pronounced. Distinct fragments of sedimentary rocks and mafic lavas are still present, but the quantity is becoming small. Striped pumices are not so common in D as are those that are brown or gray throughout. These contain large quantities of dark xenocrysts. Ordinary maximum of size of pumice is 1½ in. A minor layering, with variations of size, is visible in D.

E. 8 to 9 in. (21½ cm.) light-brown stratum.

F. 2½ in. (6½ cm.) yellow.

G. 4 in. (10½ cm.) yellow.

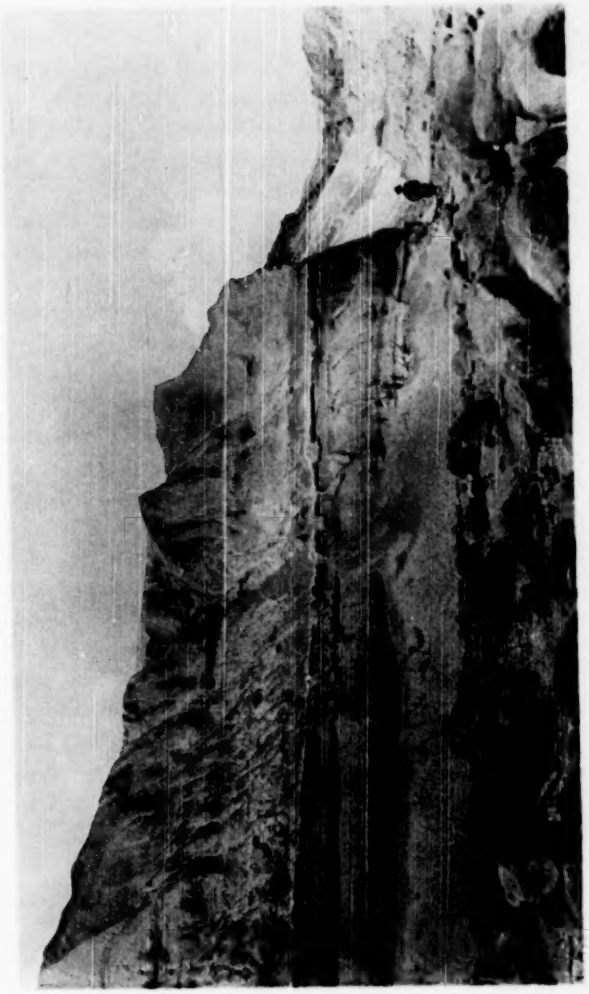
H. 2½ in. (6½ cm.) yellow.

The characteristics of these four layers are not very different from those of D. The yellow color that distinguishes F and H sharply is probably a stain, and the real color of the pumice is brown or gray. Very little white pumice in these four layers. Most pieces carry plentiful xenocrysts (set free from the lavas). Striped pumices are not nearly as numerous as those that are brown, gray, or brownish-pink throughout, though they occur. Fragments of sedimentary rocks and basic lavas are still present. In addition to variations of color there are several alternations in proportions of coarse and fine, apparently not strictly following changes of color. Ordinary maximum size is 1½ in., but pieces of 2 or 3 in. occur. Fines of wheat size fill interstices loosely as in layers below. Volcanic "scum" is not plentiful; black glass is rare or lacking.

In none of the layers A to R was black glass observed as a plentiful constituent; nevertheless, in traveling about the region much of this glass was seen, perhaps concentrated by the removal of light pumice by the strong winds. My impression was that layer D was its principal home; perhaps layers E to H also.

I. 48 in. (121 cm.) coarse gray layer. Many lumps of pumice are 2 to 3 in. in diameter, with a maximum of 4 in. (10 cm.). The average is coarser than in layers E to H. Pumice of wheat size fills interstices, but the whole of I is very loose. Dark or variegated pumices are rare. The color of the whole

Plate 1. Katmai stratified ashfall (lower half of section) overlain by Katmai incandescent tuff-flow.



is a uniform gray. There is an indistinct stratification throughout, due to variations of coarseness. In the upper one-half there is a progressive decrease of coarseness, but the separation from the next layer is not sharp. Probably I, K (and ?L) should not be regarded as separate outbursts, but as one outburst that varied in intensity.

K. 18 in. (46 cm.) fine gray layer. Characteristics are nearly those of I but size of pumice is less. A few pieces are 1 in. in diameter, but most of it is about wheat size. Loose crystals of pyroxene are abundant.

L. 21 in. (53 cm.) coarse gray layer. Like I and K, but there is a sudden increase of coarseness. Pieces 1 to 2 in. are common. Pumices are light-gray and contain dark xenocrysts. L becomes finer toward the top, but the change to much finer in M is sudden.

M. ½ in. (1.5 cm.) of fine flour; gray, stained yellow.

N. 2 in. (5 cm.) coarse sand; gray, stained yellow.

O. ½ in. fine flour; gray, stained yellow.

P. 5 in. (13 cm.) at bottom it is a grit. Contains small pumices up to pea size. At top it is a coarse sand. Color is gray, stained yellow.

Q. 3 in. (8 cm.) fine sand, not sharply separated from P.

R. 1½ in. lavender-gray mud.

On top of these layers of ashfall is the incandescent tuff-flow from Mount Katmai (plate 1). This incandescent tuff is the final phase of the eruption from Katmai, whereas in the Valley of Ten Thousand Smokes the incandescent tuff preceded the explosive eruptions from the parasitic cone of Novarupta.

In table 2 correlations are made between the two described sections of ashfall. The strata preserve their identifying characteristics from one to the other, but thickness varies somewhat. In places where a long section of ashfall is exposed minor partings are visible in the thicker strata. Some of these were indicated in the descriptions. They may have been caused either by small differences of eruptive intensity or possibly by shifting winds during the downfall.

PETROGRAPHY

The pumice samples collected from the sections of ashfall contained fragments of igneous rocks (mostly basic andesites and basalts), of sandstone and shale, of glomeroporphyritic

groups of orthopyroxene and clinopyrexene, calcic feldspars, and iron ore, and also individual crystals of these minerals dissolved out of this matrix, fragments of obsidian (black glass), and "volcanic scum" (agglomeratic crests on lava pools). With these were small loose crystals of quartz and sodic feldspar, brought in by continual influx of new magma, and

TABLE 2

Correlation of sections on northwest side of Katmai Valley.

Section No. 1	*Section No. 2*
A-175 18 in.; pure white layer; coarse, but fine at top; many lapilli.	A. 48 in.; pure white; coarse, fine at top, many lapilli.
A-176 3½ in.; terra-cotta layer; coarse at bottom to fine at top; mostly white pumice coated buff.	B. 1½ in.; white pumice coated buff; coarse.
A-177 11 in.; coarse; buff, together with white, gray, red, striped, and nearly black pumice.	C. 16 in.; light-gray or buff as a whole, but contains white, brown, gray, and striped; coarse, but finer at top.
A-178 2 in.; very like A-177 but many pieces stained bright yellow; medium fine.	D. 5 in.; yellow or orange but color is a stain; brown, gray and white pumice.
A-179 9 in.; buff; coarse, finer at top.	E. 8 to 9 in.; light-brown. F. 2½ in.; yellow. G. 4 in.; brown. H. 2½ in.; yellow. These four are not very different from D; color a stain.
A-180 50 in.; gray, but some white and terra-cotta pieces; very coarse but finer at top.	I. 48 in.; very coarse; uniform gray except some variegated. K. 18 in.; fine gray; much like I but size of pumice is less.
A-181 in.; light-gray in general, but white pumice prevails; coarse at bottom, sand at top.	L. 21 in.; coarse gray; similar to I and K but size is greater; fine at top.
A-182 8 mm.; sand.	M. ½ in.; fine.
A-183 10 mm.; grit.	N. 2 in.; coarse.
A-184 6 mm.; fine sand.	O. ½ in.; fine, some lumps.
A-185 30 mm.; grit.	P. 5 in.; coarse, fine at top.
A-186 28 mm.; sand.	Q. 3 in.; fine.
A-187 35 mm.; red-brown to purple sand.	R. 1½ in.; lavender gray.

soon disappearing as assimilation and mixing progressed. Preliminary examination in the field showed that, as the outbursts continued, the outward characteristics of inclusions recorded the effects of immersion in the lava pool. Laboratory studies enabled a somewhat quantitative evaluation of these results to be obtained. A weighed portion of each sample of the section at Camp IV was separated into various parts by sifting. Fractions passing through sieves of 10, 20, or more meshes to the inch were obtained. From these, the darker bits were picked out under a binocular magnifier, and each was placed in its proper category. Most of the quartz phenocrysts were obtained in the finer siftings, and were likewise picked out.

The constituents of the coarse lumps of pumice were not thus separated—this would have been impracticable, and also it was thought that their contents would be in about the same proportions as in the siftings.

By this method, hundreds of bits of material were separated and the weight of each group determined. The results are given in table 3. It is believed that the results express fairly closely the relative amounts of these various constituents of the ashfall and give much information on what was happening in the volcanic crater during the eruption. The inferences are supported by the chemical analyses, given later. It had become

TABLE 3

Percentage of various constituents in strata of Katmai ashfall at Camp IV.

Stratum	Andesites & Basalts	Loose Igneous Crystals	Sediments	Volcanic Obsidian	Volcanic Scum	Quartz
A-175	11.91	.06	2.6	—1.00—		.422
A-176	4.25	.56	10.0	.08	.80	.299
A-177	1.98	1.59	1.48	.64	1.90	.368
A-178	.47	4.7	.30	1.16	.66	.207
A-179	.18	4.87	.11	.116	.33	.079
A-180	.00	5.58	.21	.287	.00	.068
A-181	.03	3.48	.12	.127	.00	.032
A-185	.00	13.30	.00	.07	.00	.043

Note. For all the constituents except quartz, the figures show the percentage of the given constituent in the portion of the sample above 10 mesh (in No. A-185, above 20 mesh). For quartz the figures represent the percentage of quartz in material between 20 and 35 mesh to the whole sample. In other words, the percentage figures for quartz are comparable among themselves but not quite (though nearly) comparable with the others.

apparent in previous sections of this article that the first material erupted was a very siliceous soda rhyolite with little or no contamination by dissolved foreign material but with discrete fragments of rocks from walls. In succeeding outbursts more and more foreign material from the walls became involved and assimilated.

Table 3 shows, in approximately quantitative terms, what happened to xenoliths that became immersed in the new magma. At the first outburst the only extraneous material accompanying the white pumice was in the form of a mechanical mixture. These xenoliths were in discrete, unaltered lapilli, of which the character was easily recognizable. The lavas were andesites and basalts.

Detached igneous crystals were absent in A-175. In later strata they have become very abundant. At the same time the discrete fragments of lava are much decreased in amount. The detached crystals in these later stages are evidently due to the setting-free of phenocrysts by solution of the matrix of the mafic wall rocks. To make certain of this their characteristics in the two environments were carefully compared. Those in the lapilli were studied in thin sections microscopically, and also under a binocular magnifier in the many specimens of lapilli in which corrosion of the aphanitic groundmass had left the phenocrysts in relief.

In the second environment the phenocrysts that had been set free occurred either in lumps of pumice, or as inclusions in obsidian or "scum," or as loose crystals, and were studied by the same methods as were applied to the lapilli. The characteristics in the two environments were identical. The crystals of the mafic minerals, singly or in groups, have certain characteristics of size, form, and association, and these characteristics appeared unmistakably the same in the pumices as in the lapilli of andesite and basalt.

The processes of attack upon the xenoliths involved either an intimate penetration and consequent softening of the whole mass, followed by dispersal of the phenocrysts, or the breaking-up of the fragments by attack along fissures, simultaneously with solution of the groundmass around the periphery. The glass surrounding xenoliths and xenocrysts has become streaked with brown threads. Finally, multitudes of phenocrysts of the kind that the xenoliths carried are found in the later strata

of the ashfall, though the earlier strata are practically free of them.

The phenocrysts of the pumices are thus identified with those of the lavas of the former crater walls.

Bits of sedimentary rocks appeared in considerable force in the first two outbursts, and then nearly disappeared, leaving little trace. The reason for this will appear in connection with the analyses.

Quartz, in small crystals, was present from the first as an accompaniment of the new rhyolite, but even at this early stage many of the quartz phenocrysts were embayed by corrosion. The quantity rapidly decreased, but a small amount continued to appear throughout the series. It is inferred that it was resorbed rapidly, but that the supply was continually replenished by new rhyolite magma that kept welling up into the crater. This new rhyolite did not become thoroughly mixed up with the contaminated magma at once, but, still unmixed or partially mixed, it was ejected in the explosions and showed up in the ashfalls as separate lumps of white pumice or in the black-and-white striped pieces. It is accompanied by sodic plagioclase. Even in stratum A-185, in which so much mafic rock had been assimilated that the silica content had dropped to less than 58% (on a non-volatile basis), careful treatment with H_2SO_4, HF, and HNO_3 dissolved everything except quartz and left a considerable number of quartz crystals.

The presence of quartz in the new rhyolite supplies information on the upper limit of temperature, when the lava first rose. The transition point between quartz and tridymite is 870° C. If the quartz phenocrysts had been formed at considerable depth the transition point would have been raised, but probably not higher than 1000° C.; that is, the magma was not greatly superheated. Its ability to dissolve xenoliths cannot be attributed to excess temperature at the beginning but must be laid to the development of heat by exothermic reactions.

The new magma A-175 contained a little primary plagioclase. Its indices showed Ab_6An_1, oligoclase-albite, appropriate to the rhyolite. The small crystals were rather more numerous than those of quartz. They were likely to crumble when picked out of the pumice, and were often surrounded by a mixture of

crystal fragments and glass. Although there was no contamination in A-175, the quartz and plagioclase crystals thus showed signs of resorption. Exothermic reactions had already induced instability.

In the hybridized pumices phenocrysts (xenocrysts) of more calcic plagioclases were abundant. They show a wide range of composition, as was appropriate for the variety of andesites and basalts that are believed to have been dissolved. The extremes range from An_{27} to An_{82}. The manner in which feldspar and pyroxene crystals in the "scum" became riddled with glass has been described on a previous page. Some of the feldspars picked out of the pumices showed the same sort of attack. The composition of feldspars was considered especially important as an indication of the nature of the basic rocks in which they had their original home, and many determinations were made. Although the indices varied widely, the majority clustered around a value indicative of a mineral on the border line between labradorite and andesine, or An_{55}($SiO_2 = 54$ per cent). From previous studies of many of the older lavas of the Katmai region, this feldspar would be appropriate for a rock of about the same silica content, or 54 per cent. If the inferences toward which everything points are correct, the basic members should be a rock or mixture of rocks of approximately 54 per cent silica. Confirmation of this in other ways will be given in the section on Analyses.

It was such a rock or mixture that was assimilated by the new rhyolite magma to give the service of hybrid pumices. The sedimentary rocks that also became involved in the new magma are left out of consideration. It has been shown that after ejection of fragments of them in the first two explosions little trace of them was to be seen. The analyses will confirm this. The igneous lapilli of the first explosions likewise disappeared as such, but their phenocrysts appear as xenocrysts in the later ejecta. At the same time solution of their groundmass and corrosion of the phenocrysts have resulted in a higher index of the glasses of the later pumices. The amount dissolved became mixed with the rhyolite, and therefore the mixture was not as basic as would be appropriate for the original groundmass of the phenocrysts. As a result the phenocrysts of the pumices are those of andesites or andesitic basalts, but they are enveloped in a glass that is not in accord. Its index in the major stratum

A-180, for instance, is that of a glass of 71 to 72 per cent silica content, with striae of higher index running through it. These striae are like those that appear as defects in the manufacture of optical glass when a melted batch has not been sufficiently stirred to smooth out inhomogeneities caused by attack on the pot walls.

(*To be continued*)

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THE NATURE AND RELATIONSHIPS OF THE PALEOZOIC MICROSAURS

ALFRED SHERWOOD ROMER

ABSTRACT. An attempt is made to establish a series of characters whereby the small Paleozoic tetrapods usually termed microsaurs may be defined. A considerable number of Carboniferous and early Permian genera belong to this category, but other genera which have frequently been included do not pertain. Although the "type" microsaur, *Hylonomus*, is among the forms excluded, it seems best to retain the familiar ordinal term Microsauria for the group as here defined. The microsaurs appear to have no relationship to reptiles, but are possibly ancestral to the urodele and apodous amphibians.

FOR a number of years I have been engaged in a review of our knowledge of the older, pre-Jurassic fossil Amphibia, attempting to place them in a reasonably consistent phylogenetic and systematic framework—this not as a definitive arrangement, but with the aim of furnishing a point of departure for future work. I have from time to time made "reports of progress" in one form or another (as in Romer, 1940, 1941a) and have incorporated the results of the earlier stages of this work in the revision of my text in vertebrate paleontology (1945a). I have recently reviewed the Labyrinthodontia in rather comprehensive fashion (1947).

There remains for consideration a second major group. This I have called the Subclass Lepospondyli, using this term in a very broad sense to include the existing Urodela and Apoda (Gymnophiona) as well as various ancient fossil forms. In the labyrinthodonts the vertebral centra appear to have ossified from varied cartilaginous "arch" centers; in the lepospondyls the centrum is characteristically a spool-shaped unit structure, formed, it would seem, as a direct ossification in a mesenchyme sheath about the notochord.

A very considerable amount of material has been assigned, from time to time over the past century, to the various Paleozoic groups which I include in the Lepospondyli. Our knowledge of these forms is, however, quite unsatisfactory in almost every instance. Most are animals of small size, with a body length, generally, of but a few inches. This in itself tends to make accurate observation difficult. A majority are preserved in flattened, two-dimensional form, frequently on slabs of

shale or "cannel"; this adds a further handicap. Specimens from the Coal Measures constituting a considerable proportion of the material, are frequently "diseased" through the presence of pyrite, and tend to disintegrate, thus making it impossible to verify or amplify the studies (often superficial) of the original describer. Much of the material is fragmentary in nature—disembodied heads, headless trunks, disarticulated partial skeletons, often with dubious association of various elements. As a consequence our knowledge of the Paleozoic lepospondyls is tantalizingly inadequate, despite the attention paid them in early days by such men as Dawson, Huxley, Cope, Fritsch, and Credner, and even despite valuable revisionary studies of recent years, of which those of Steen are outstanding.

A plethora of names, mainly of ordinal character, has been applied to the various components of this ancient lepospondyl assemblage. A pattern which many have followed, and to which I have very tentatively adhered, was established as a result of the report of the Miall Committee (on which Huxley presumably played an important role). In this report (Miall, 1875, p. 151) most of the amphibians to be considered here were ranged in three groups: Nectridia, Aistopoda, and Microsauria. The Nectridia are, despite skull modifications, a clear-cut group, abundant in the late Pennsylvanian and surviving into the early Permian; the double fan formed by neural and haemal arches of the caudal vertebrae is an unmistakable nectridian trademark. The group Aistopoda was formed to care for two elongate, eel-like or snake-like types found in the Carboniferous, of which *Ophiderpeton* and *Dolichosoma* are representative. There is little or no evidence that the two are related rather than parallel (cf. for example, J. T. Gregory, 1948b), but we will not concern ourselves here with this problem.

DEVELOPMENT OF THE MICROSAUR CONCEPT

In the year 1853 a paper by Lyell and Dawson (with addenda by Owen and Wyman) announced the discovery of the remains of tetrapods in tree stumps at the famous Carboniferous locality at the Joggins, Nova Scotia; Dawson published a number of later papers on additional finds. The material has been restudied by Miss Steen (1934) (who gives references to the earlier literature). Much of it pertains to a small

rhachitomous amphibian, *Dendrepeton*, but in addition there are various more obscure remains to which a variety of names has been given. One named form is of importance here—the genus *Hylonomus*, with *H. lyelli* as the genotypic species. The type material is that of a small animal which Dawson believed to show reptilian affinities. For its inclusion he erected the group Microsauria. This term was retained by Cope (1869, p. 9) and by the Miall Committee in 1875; they, however, in opposition to Dawson, considered the Microsauria as amphibians rather than reptiles—an opinion followed by most (but not all) later writers.

Until this time, no forms other than those represented by Joggins material had been included in the Microsauria. Now, however, began Fritsch's classic studies of the fauna of the "Gaskohle" of Bohemia, the results of which were published in four quarto volumes beginning in 1879. Among the tetrapods from Nyran and other localities in the Stephanian of Bohemia were a number of small forms—as *Microbrachis*, *Hyloplesion*, *Seeleya*, *Sparodus*, "*Limnerpeton*"—which he associated with the Microsauria; in fact, certain remains were included in the typical genus *Hylonomus*. There followed Credner's work on the equally famous European Lower Permian locality of the Plauen'schen Grunde near Dresden. Certain small tetrapods—"*Hyloplesion*," *Petrobates*—from this locality were interpreted by Geinitz and Deichmüller (1882) and by Credner (1885, 1890) as related to Fritsch's and Dawson's microsaurs and indeed one of the two forms concerned was assigned (on very slight grounds) by Credner to Dawson's genus *Hylonomus*. In this country, Cope described the fauna of the Linton (Ohio) cannels (1875, etc.); most amphibians from this deposit are labyrinthodonts, nectridians or aistopods, but many of the Linton forms have been referred at one time or another to the microsaurs (Moodie, 1916, Romer, 1930, Steen, 1931). Unpublished work by L. I. Price indicates that a number of small Texas Lower Permian tetrapods, often confused with the captorhinomorph reptiles, are related to the supposedly characteristic microsaurs—these including *Pariotichus* (s.s.), *Cardiocephalus*, *Gymnarthrus*, *Euryodus*, and possibly others. Still further forms have been assigned to the general microsaur category by one writer or another. Most workers treating of this assemblage of forms have retained Dawson's name

Microsauria, although the writer (1933, pp. 112, 436) used Micramphibia as more appropriate. Watson (1929) in describing some small skulls from the Scottish Lower Carboniferous—*Adelogyrinus*, *Dolichopareias*—coined the new ordinal name Adelospondyli. This term, applied primarily to the Scottish genera and to *Lysorophus* of the American Permian, was mainly based on the fact that in these forms, in contrast to various other lepospondyls, neural arch and centrum are sutturally separate. However, Miss Steen's work (1938) shows that this sutural situation is spread widely but sporadically and variably through much of the extent of the microsaurs. As Westoll notes (1942a) the neurocentral suture proves to be an unreliable taxonomic character, and Adelospondyli appears to be essentially a synonym of Microsauria—as this term is currently used. Although various authors have made various additions or subtractions, the circle of forms currently regarded as belonging in the Microsauria is essentially that given by me in the recent edition of my text (1945a, pp. 591-592).

THE MICROSAUR CONCEPT

The current microsaur concept embraces a variety of tetrapods, mainly from the late Pennsylvanian but extending downward stratigraphically into the Mississippian and upward into the Lower Permian. All are of small size—many are tiny. All appear to have spool-shaped, "holospondylous"— *i.e.* lepospondylous—vertebral centra, and in this are in contrast with typical labyrinthodont amphibians. We may note that in distinction from other lepospondyls the vertebrae lack the peculiar fan-shaped caudal arches which are the trade-mark of the nectridian; the body shape, where known, is relatively normal and hence in contrast with the snake-like types currently placed in the Aistopoda (*Lysorophus* and its allies, if considered microsaurs, are atypical in this as well as other regards). Beyond these few obvious features there is at present in the literature no further definition of a microsaur. This situation suggests that we are dealing with an amorphous, ill-defined assemblage with nothing to guarantee that it is a natural unit. Further, there is little to distinguish microsaurs on this basis from the reptiles—a point of major importance, since confusion may occur (and has occurred) between the

two groups, and since at various times part or all of the microsaurs have been claimed to be reptiles or related to them.

We shall not at this point concern ourselves with the nature of the Nova Scotian *Hylonomus* "type" of the microsaurs, for, as we have noted, the concept of the group Microsauria rapidly passed from one based on *Hylonomus* to one derived from a series of forms, mainly European, which are not necessarily similar to *Hylonomus* (and, as noted elsewhere, are apparently quite distinct). Of such forms *Microbrachis* of the Stephanian of Nyran is the best known, since it is represented by abundant material which has been carefully redescribed by Miss Steen (1938, pp. 227-234, figs. 15-20, plates 1, 3). *Microbrachis* has certain characters of the skull table which are not repeated in other microsaurs and hence may be recognized as specializations; it otherwise appears to occupy a reasonably central position in the modern concept of a microsaur (and is so considered by Westoll, 1942b). Features seen in *Microbrachis* and its close allies which can be of aid in deciding whether or not other forms belong in the same broad category are here listed and commented upon.

1. *Size small.* The specimen restored by Steen has a length of about 12 cm.; some individuals of *Microbrachis* were moderately longer. This size appears to be about an average for Carboniferous microsaurs (some terminal Lower Permian forms were considerably larger).

2. *Body moderately long and slender. Microbrachis* and various other microsaurs have rather salamander-like proportions, with an elongate trunk (here about four times the skull length); a high number of presacral vertebrae (here 38 presacrals, but a somewhat lower count in other known cases); rib contours indicating a relatively narrow trunk.

3. *Spool-shaped vertebral centra; no trunk intercentra; caudal chevrons?; neural arch pedicel relatively high and narrow anteroposteriorly; neural arch not expanded transversely nor swollen; neural spine little developed.* The vertebrae and ribs of *Microbrachis* are figured by Steen (1938, fig. 19C) and Schwarz (1908, fig. 35). In various other microsaurs the centra may be less elongate; cf. for example, Fritsch, 1879, plate 40, fig. 1 (*Seeleya*). Trunk intercentra have not been reported in any form here regarded as a microsaur; it is, however, not impossible that such structures were present in

cartilage in some cases. Steen reports poorly preserved caudal chevrons in one specimen of *Microbrachis*. Since, however, they do not appear in other individuals of this or in related forms, and since some confusion with caudal ribs is not impossible in a small and poorly preserved specimen, judgment may be suspended on this feature. The narrow base of the neural arch and lack of any degree of spine development is a striking feature of Nyran microsaurs in general, as may be seen in various of Fritsch's figures on his plates 37, 39, 40, 44, etc. There is no evidence in the material of the expanded, swollen type of neural arch so typical of the cotylosaurs and of the seymouriamorphs.

4. *Ribs two-headed, capitulum often articulating with facet or low process on the centrum, tuberculum articulating with transverse process.*

5. *Interclavicle with very broad but short fan-shaped head and short slender stem.* The girdles are too poorly preserved in most microsaurs for accurate diagnosis. The interclavicle is, however, of a unique type; see Steen, 1938, fig. 19B; Fritsch, 1879, plate 47, figs. 1-3.

6. *Limbs relatively short and feeble; manus three-toed.* The limbs of *Microbrachis* and of such other typical microsaurs as have at all adequate limb material preserved are relatively short and slender compared with those of many labyrinthodonts and are seen to be especially feeble if compared with those of contemporary reptiles. That the three-toed nature of the manus of *Microbrachis* is not exceptional or based on faulty material appears to be confirmed by a similar three-toed condition in *Hyloplesion* (Steen, 1938, fig. 22A).[1]

7. *Scales with a characteristic radiate striation; ventral scales sub-oblong, with a pronounced posterior ridge; dorsal scales rounded.* This type of radiate scale ornamentation is, as far as I am aware, confined to microsaurs and is widespread in this group. The scales of *Microbrachis* (Fritsch, 1879, plate 47) are slightly atypical in that the ridges of the striate pattern are heavier and coarser than is normal; for other and perhaps slightly more typical scales from Nyran, cf. Fritsch, 1879, plate 32, figs. 2, 5; plate 35, figs. 5-7; plate 37, figs. 1, 9-11; plate 39; plate 40; plate 41, figs. 2, 3, etc. In some cases (as

[1] I know of no evidence for the restoration by Fritsch (1879, figs. 94, 103, 105, 108, 112) of microsaurs with a five-fingered hand.

Sparodus crassidens, Fritsch, 1879, plate 10) the pattern may assume a more circular rather than a radial arrangement.

8. *Skull greatly elongate postorbitally; otic notch absent.* In the series crossopterygians-amphibians-reptiles there has been, as pointed out by Westoll (1938) and the writer (Romer, 1941b, pp. 156-159, fig. 4) a notable shift in skull proportions as regards the relative length of the preorbital and postorbital segments; there has been, along this main evolutionary line, a steady reduction of the relative length of the postorbital region

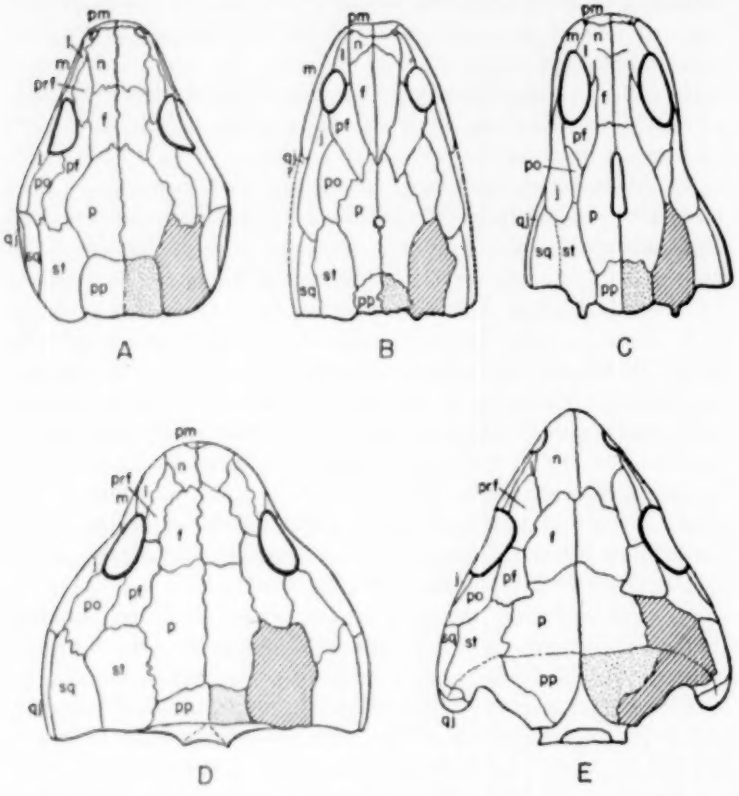

Figure 1. Dorsal views of various microsaurs: *A*, *Euryodus*, *B*, *Dolichoparcias*, *C*, *Adelogyrinus*, *D*, *Pantylus*, *E*, *Ostodolepis*. Abbreviations: *f*, frontal, *j*, jugal, *l*, lacrimal, *m*, maxilla, *n*, nasal, *p*, parietal, *pf*, postfrontal, *pm*, premaxilla, *po*, postorbital, *pp*, postparietal, *prf*, prefrontal, *qj*, quadratojugal, *sq*, squamosal, *st*, supratemporal, *t*, tabular. On right side, supratemporal hatched, postparietal stippled. *A* after Olson, *B*, *C* after Watson, *D* composite of various specimens, *E* after Case.

(disregarding obviously secondary reversals among certain temnospondyl labyrinthodonts). The short face and long postorbital region of *Microbrachis* (and other microsaurs) shows a remarkably primitive condition (figs. 1, 2).

9. *Skull roofing pattern generally primitive, but tabular absent from roof and a very large supratemporal interposed between parietal and squamosal.* The pattern of the temporal region, when preserved, offers the best diagnostic character of this group (figs. 1, 2). In various other amphibians—notably the Rhachitomi—there is a trend for reduction of bones on the skull table, so that in addition to loss of the intertemporal the posterior elements may undergo reduction at the expense of the more anterior ones. But in no known labyrinthodont is the tabular completely excluded from the skull roof; here it is absent in all known cases, although the postparietal persists dorsally. In contrast to the reduction of the tabular we find the supratemporal highly developed as a major component of the skull roof.

In regard to the skull table *Microbrachis* (fig. 2B) appears to be somewhat aberrant; such a form as *Euryodus* (fig. 1A) shows what is apparently a more primitive condition. In such forms the postparietals, strongly reduced in *Microbrachis*, are persistently large. Further, while the supratemporal is a large

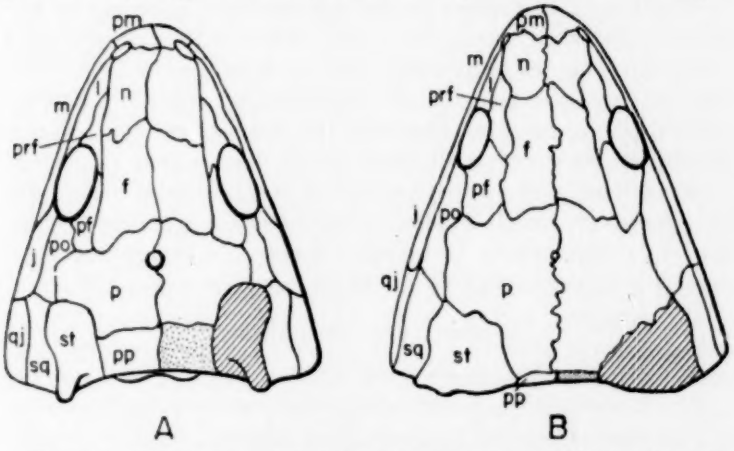

Figure 2. Dorsal views of skulls of *A*, *Hyloplesion*, *B*, *Microbrachis*. Abbreviations and conventions as in figure 1. *A* partly after Steen, posterior elements restored from Fritsch's data; *B* after Steen, but postparietal (present in smaller individuals only) retained.

element in *Microbrachis*, it is still more prominent in other microsaurs shown in figs. 1 and 2, stretching forward to a broad contact with postfrontal and postorbital—a contact almost entirely lost in *Microbrachis*.

Whether the element here termed supratemporal is really that element or the tabular is not, of course, entirely certain (particularly in the absence of knowledge of the occiput in most microsaurs). But presumably the process of modification in skull table pattern was parallel to that seen in certain labyrinthodonts, in which the tabular may be nearly pushed off the skull roof, while the supratemporal remains an element of substantial size (Romer, 1947, fig. 22, etc.). It is important to note that in these labyrinthodonts the postparietal is reduced *pari passu* with the tabular, whereas in microsaurs the former element is much more resistant to reduction.

10. *Palate essentially primitive in nature, with slender cultriform process of parasphenoid; movable basal articulation of braincase and palate, narrow interpterygoid vacuities.* Unfortunately little is known of braincase structure in *Microbrachis* or indeed in any microsaur. The occipital condyle (unknown in *Microbrachis*) appears to have been generally primitive in nature—technically single, but broadened and trending (as in other amphibians) toward the double type.

The items listed above give us a diagnosis which may be applied to Paleozoic tetrapods as a possible test of inclusion in or exclusion from the microsaur group. It is unfortunate that this list of characters seen in *Microbrachis* is incomplete and to some degree superficial. However, the forms to be surveyed are in almost every case still more poorly known than is *Microbrachis* itself and we must grasp at any available straw. Of the characters listed, the skull table pattern is apparently most useful in cases where the skull is known; in fragmentary or poorly preserved material, the scale type is a useful clue.

IDENTIFIABLE MICROSAURS

1. *Microbrachis*, as discussed above.

2. *Hyloplesion.* In the late Pennsylvanian Gaskohle fauna of Bohemia described by Fritsch, a number of other microsaurs are identifiable. Best known is *Hyloplesion longicostatum*, represented by complete skeletons as well as more fragmentary materials (Fritsch, 1879, pp. 160-161, plate 27, fig. 5; plate

36, fig. 2; plates 37, 38; plate 39, figs. 1-9; Steen, 1938, pp. 234-237, figs. 21, 22, 44B; plate 1, fig. 1; plate 4, fig. 3). In general the skull is quite similar to that of *Microbrachis*. Steen figures a small tabular, but this interpretation is certainly questionable and Fritsch's figures and galvanotypes strongly suggest that the supratemporal extended back to the posterior end of the table as in other microsaurs (fig. 2A). *Hyloplesion* is less specialized than *Microbrachis* in that the postparietals are well developed. The postcranial skeleton, including vertebral count and structure, squamation, etc., all agree well with *Microbrachis*. The presence of a three-toed manus, as in that genus, may be noted.

3. "*Limnerpeton*." This genus of Fritsch's is a dumping ground for poorly known amphibians. Some of the remains are those of labyrinthodonts (Romer, 1947, pp. 143-144) and some are quite obscure.[2] A majority of the *Limnerpeton* species seem, however, to fit in well with the microsaur pattern in scales, vertebrae and other details. Such are: *L. macrolepis*, *L. elegans* and *L. obtusatum* (Fritsch, 1879, plates 32-35, etc.).

4. *Seeleya* (Fritsch, 1879, plate 40, fig. 1; plate 41, figs. 1-3). This is a very tiny Nyran form, obviously pertaining to this group but with relatively short vertebrae. *Orthocosta* (Fritsch, 1879, plate 39, figs. 10, 11; plate 44, figs. 1-3) is a probable synonym.

5. *Sparodus*. Somewhat more doubtful is this genus (Fritsch, 1879, plates 8-10). Two species are described; their congeneric nature is none too certain. *S. crassidens*, from Kounova, exhibits microsaur squamation. Both, but particularly *S. validus* from Nyran, have a strong palatal dentition which was compared by Cope (1881, p. 79) with that of *Pantylus* of the American Permian.

6. *Ricnodon*. The fragmentary material assigned to this genus by Fritsch (1879, pp. 167-171, figs. 106-108, plates 42, 43, 44, figs. 4-15) shows microsaur vertebrae and scales. However, the skull described by Watson and by Steen (1938, p. 227, figs. 13, 14, plate 7) as *R. limnophyes* is not microsaurian in nature and evidence for assignment here is very weak.

[2] "*Limnerpeton*" *laticeps* (Fritsch, 1879, plate 36, fig. 1) is strikingly similar to *Amphibamus* and *Miobatrachus*, presumed ancestral "frogs."

7. "*Hylonomus*" of Niederhässlich. Certain small tetrapods present in the early Permian Niederhässlich deposits near Dresden, first described by Geinitz and Deichmüller (1882, plate 8, figs. 1-9) were identified as belonging to Fritsch's genus *Hyloplesion*. Credner (1885, pp. 724-736, plate 29) assigned this material to Dawson's genus *Hylonomus* (quite incorrectly, one may believe); later, however, he realized that two quite distinct animals were represented. One, *Petrobates*, will be considered later; the second he termed *Hylonomus geinitzi* (Credner, 1890, pp. 240-247, 255-258, plate 9, figs. 1-11), pointing out, however, its close similarity to Fritsch's *Hyloplesion*. This animal (once the *Petrobates* material is sorted out) conforms in most regards to the typical microsaur structure defined earlier. The vertebrae and clearly dichotomous ribs are comparable to those of *Microbrachis* and *Hyloplesion*. Intercentra are absent; so too are haemal arches in the tail. Credner's plate 9, figure 5 indicates a vertebral count of close to 30 presacrals (despite his own statement that the count was much lower). Several of Credner's figures show the characteristic fan of the interclavicle, and a low degree of development of limbs, much as in *Microbrachis* and *Hyloplesion*. The scales are closely comparable with those of *Hyloplesion*. It may be noted, however, that in addition this form has a series of tiny polygonal bony plates in the region of the pectoral girdle (Credner, 1890, plate 9, figs. 6, 9, 10, 's'). The skull is poorly preserved but Credner's plate 9, figure 6 shows clearly the presence of three elements lateral to the parietal—obviously the characteristic large supratemporal in addition to squamosal and quadratojugal.[3]

8. *The gymnarthrids*. Vertebrate specimens from the early Permian Redbeds of the American Southwest are preserved in a fashion quite different from those of the European deposits so far discussed. Instead of slabs of shale on which small skeletons may be preserved but skulls crushed, the usual matrix is a clay from which recovery of tiny skeletons is unusual but in which skulls may be preserved in three-dimensional fashion. In consequence we deal here mainly with skull material. Parenthetically, we may note that these terminal members of the

[3] The restored composite skull figured as that of "*Hylonomus geinitzi*" by Watson (1940, fig. 11) does not agree with this; it is, however, of a type to be expected in *Petrobates*.

microsaur group tend (as do other contemporary lepospondyls) to relatively (although not absolutely) large size.

The typical microsaurs of the American Redbeds are a series of forms which include *Pariotichus, Gymnarthrus, Cardiocephalus, Euryodus and Isodectes;* they are known almost entirely from skull materials, these skulls averaging about 2 cm. in length. Most recently described is *Euryodus* (Olson, 1939); a resumé of the older material was given by Case (1911a, pp. 69-70, 144-145; 1911b, pp. 34-35, 36-38, 91-93). Mr. L. I. Price informs me, as a result of his unpublished studies of the group, that all are very similar in cranial structure despite variations in description. The skull pattern, as seen in *Euryodus* (fig. 1A) or *Pariotichus*, is exactly that to be expected in a typical microsaur—a short face, a very long, postorbital region, good postparietals but no tabular in the skull table, and a long and highly developed supratemporal reaching forward to a broad contact with both postorbital and postfrontal. The palate, as in other microsaurs, is one with a narrow cultriform process of the parasphenoid, movable basal articulation and narrow interpterygoid vacuities. The teeth are, in this group, blunt and medio-laterally compressed. As in certain, at least, of the other microsaurs there is no indication of emphasis of the "canine" region in the anterior part of the maxilla; instead there is here a trend toward tooth enlargement in the posterior part of the maxillary series.

9. *Ostodolepis.* Other microsaurs, less typical in nature but definitely members of this group, can be identified in the Redbeds fauna. One such is *Ostodolepis.* This was first described by Williston (1913) on the basis of vertebrae; Case later (1929) described a nearly complete skeleton. A striking peculiarity lies in the skull shape, with a domed roof and curiously pointed "snout." Case, in summarizing the features of *Ostodolepis*, found himself puzzled to assign this form to either reptiles or amphibians since it seemed to him to show many features characteristic of both classes. However, the more important of his supposed reptilian characters—such as the palatal construction—are now known to be primitive amphibian characters retained in microsaurs as in reptiles.

The skull, despite its obvious peculiarities, shows the definitive microsaur characters (fig. 1E): absence of tabulars from the skull roof, but retention of postparietals (here slanting

backward on the occipital surface), and a highly developed supratemporal running from postorbital and postfrontal to the back of the skull. Ossified hyoids are present. The vertebrae are "holospondylous"; there are no intercentra[4] nor is there space for them; the neural arches are not broadened nor swollen. The imperfectly preserved interclavicle has (Case notes) an extraordinarily broad head, and thus is probably of microsaur type. The limbs are relatively small. There is preserved a system of ossified scales which Case compares with those of the microsaur *Sparodus crassidens* of Fritsch.

10. *Pantylus.* The genus *Pantylus*, mainly known from skull material from the Texas Permian Redbeds, has long been a puzzle to paleontologists; Williston (1916, pp. 165-176) is the most recent describer. The lack of an otic notch and its relatively large size (reaching a skull length of 9-10 cm.) have caused most authors to place it among the cotylosaurs. It does not, however, conform readily to the structural pattern of any cotylosaur group, and its specialized dentition, with a battery of blunt crushing teeth, tends to further isolate it. Restudy indicates that it is unquestionably a (relatively) large end form among the microsaurs, and is obviously related to *Sparodus* of earlier European deposits (Cope, 1881, p. 79; Romer, 1945b, p. 429). The proportions of the skull roof are typically microsaurian. Williston was unable to determine the pattern of the skull table; comparative study of all available material indicates the presence of the microsaur pattern shown in figure 1D. As in other members of the group, the palate retains a movable basal articulation, and interpterygoid vacuities are small. Vertebrae presumably associated are comparable to those of *Ostodolepis*. If the caudal vertebrae figured by Williston are actually those of *Pantylus* they are of considerable theoretic interest in bearing haemal chevrons. The limbs, incompletely known, were very small; plates in the form of tiny tesserae covering part of the belly are comparable to those noted for the Niederhässlich "*Hylonomus*."

11. *Tuditanus?* Curiously, identifiable microsaurs from the Carboniferous are as rare in North America as they are abundant in Europe. Several forms thought to be microsaurs are (as noted later) true reptiles. Of the three major American

[4] The supposed intercentra of Williston's type are not such but are apparently rib fragments.

Pennsylvanian tetrapod localities—Mazon Creek, the Joggins, and Linton—no microsaurs are identifiable from the first and none is positively known from the second (although very probably present). Even at Linton there are few specimens which can even be considered for entry into this category, for most of the forms termed microsaurs by Moodie (1916) have since been shown by Steen (1931) or the writer (1930,1947) to belong elsewhere or are peripheral, rather than typical members of the microsaur group. The only specimens which merit consideration are the type of *Tuditanus punctulatus* and a second specimen which Cope assigned to this species but was made the type of *Eosauravus copei* by Williston (Cope, 1874, pp. 271-272; 1875, p. 392, plate 34, fig. 1; 1897, pp. 88-90, plate 3, fig. 1; Williston, 1908, pp. 395-400; Moodie, 1909, pp. 11-16, plates 4, 5; 1916, pp. 55-88, fig. 19; Romer, 1930, pp. 134-135, etc.). The type specimen of *T. punctulatus* consists of the anterior part of the body of a small tetrapod; the second, type of *Eosauravus*, includes much of the trunk and tail but lacks head and anterior limbs. The *Eosauravus* specimen was hailed by Williston as "the oldest known reptile" and is generally considered as reptilian; little attention has been paid to the *T. punctulatus* type, and there is no guarantee that the two are associated. Little can be made of the skull, and squamation is absent from both specimens. Evidence for reptilian nature is the assumed hind leg phalangeal formula of 2.3.4.5.4, possible presence of more than three digits in the manus and of two sacral ribs, and the presence of a stemmed interclavicle. But there is no evidence of five phalanges in toe four, and certain microsaurs have a five-toed pes with nearly as high a formula; further, it is not impossible to interpret the interclavicle as of the peculiar type seen in *Microbrachis*, etc. Arguing for a microsaurian position are the long and slender body proportions; it is clear that both specimens of *Tuditanus* must have had a higher presacral count of vertebrae than is found in early reptiles. Again, caudal chevrons appear to be absent. Still further, if Moodie is correct as to orbital position in his figure of the *Tuditanus* skull, the long postorbital region is indicative of microsaur rather than reptilian structure. More evidence is needed, but *Tuditanus* is not improbably a microsaur.

12. *Dolichoparcias*, *Adelogyrinus*. Among the few known

amphibians of Mississippian age are two types of modest size represented by skulls and in one instance by some postcranial remains including "holospondylous" vertebrae (Watson, 1929, pp. 245-250, figs. 24-27). In both genera (fig. 1B, C) the "face" is extremely short, the postorbital region much elongate, in a fashion both primitive and comparable with that of later microsaurs. In correlation with this elongation, the postorbital bone has been dragged backward out of the orbital margin (cf. *Colosteus*, *Erpetosaurus*). In both (again as in microsaurs) postparietals are well developed, but tabulars are absent from the skull roof. In both we find instead—as in microsaurs—a single elongate element lateral to the parietal and postparietal extending from the postorbital to the back margin of the skull.[5] In *Dolichopareias* the lateral margin of the cheek is unknown, but we can reasonably regard this element as the supratemporal and assume both squamosal and quadratojugal to have been present more laterally. In *Adelogyrinus* no suture is evident between supratemporal and squamosal, a single large element occupying the position of the two. These two genera may be reasonably considered as early forerunners of the microsaurs.

The microsaur periphery. So far we have confined our survey to forms exhibiting, as far as can be determined, the characteristic features of the microsaurs defined above. There are, however, various other lepospondylous forms of the Carboniferous and earlier Permian which may be allied to the microsaurs and may perhaps be included in a broad common group with them. These may be noted in passing.

It will, I think, be generally agreed that the varied nectridians form a distinct category of lepospondyls. There remain, however, three further series of amphibians, all elongate eel-like or snake-like forms, which are lepospondylous but nonnectridian and hence possibly of microsaur affinities. The *Ophiderpeton* and *Dolichosoma* groups, of ancient lineage, but poorly known, are customarily included (for no particular reason) in a common, distinct group, the Aistopoda. A third series of elongate forms, of which *Lysorophus* of the early Permian is best known, is, in contrast, often included in the microsaurs, and definitely included in Watson's Adelospondyli.

[5] There is no positive evidence of a tabular, despite its restoration by Bystrow (1935).

Lysorophus, however, is a very specialized form which shows few of the features cited above as characteristic of the microsaurs (cf. J. T. Gregory, 1948a, p. 564) and there is as little—or as much—reason for its inclusion here as for the inclusion of the aistopods.[6] If these forms are related to the typical microsaurs, as may well be the case, the relationship is a distant one and discussion of this matter is not pertinent to our present purposes.

TRUE REPTILES CONFUSED WITH MICROSAURS

It is obvious that the microsaurs have many features in common with the reptiles—features which have led various people to advocate their relationship to reptiles or even their inclusion in that class. Putting aside for the moment the problem of possible relationship, it is of importance to see how a microsaur can be distinguished from forms which would be agreed to by all to be definitely reptilian. *A priori*, it is highly probable that confusion between two such groups, whether related or not, might readily take place. It was once thought that reptiles made their appearance at about the beginning of the Permian; but various instances of the occurrence of true reptiles are now known well down in the Carboniferous and the finding in the Pennsylvanian of such specialized reptile types as *Edaphosaurus* and diadectids indicates that the origin of the Reptilia is to be looked for well back in the Pennsylvanian. We must be on the outlook for small Carboniferous true reptiles which, if poorly preserved or insufficiently described, might be included among the microsaurs.

If the list of microsaur characters cited above be examined, it is obvious that certain of them are found both in this group and in forms generally accepted as genuine reptiles. Both have "holospondylous" vertebrae; the ribs are similar; the microsaurs, like reptiles, have retained an essentially primitive type of palate contrasting with that of most amphibians; neither typical microsaurs nor primitive true reptiles have taken on the eel-like proportions of certain amphibian types; most reptiles have, like microsaurs, eliminated the otic notch; typical microsaurs are much smaller than the average of known early reptiles, but size is no safe criterion.

[6] As I hope to show at another time, *Lysorophus*, sometimes thought to be an ancestral urodele, is a reasonable ancestor of the Apoda.

Other features may, nevertheless, aid us in distinguishing between the two groups. On the basis of present knowledge, the presacral intercentra are indicative of a reptile rather than a microsaur, and the presence of haemal arches is perhaps diagnostic as well. Early true reptiles are all relatively short and stocky, with no more than 27 presacral vertebrae, and with stoutly developed limbs; all microsaurs in which the body form is known have much more slender and elongate trunks, with a higher presacral vertebral count (usually in the 30s) and with limbs of smaller size.[7] The pes of microsaurs is of a pentadactyl type not dissimilar to that of reptiles; the manus, in contrast, has but three digits in known instances.

The squamation is highly distinctive. The typical microsaurs have well developed ornamented ventral (and dorsal) scales; in reptiles there is a ventral "abdominal rib" system with the scales reduced to oat-shaped or rod-shaped elements.

The skull, if well preserved, can exhibit strongly contrasting features (cf. fig. 3 with figs. 1, 2). The microsaur skull is exceedingly primitive in its elongate postorbital region; reptiles are notable for major reduction proportionately of the

[7] Even discounting the greater slenderness of limb elements to be expected in small animals.

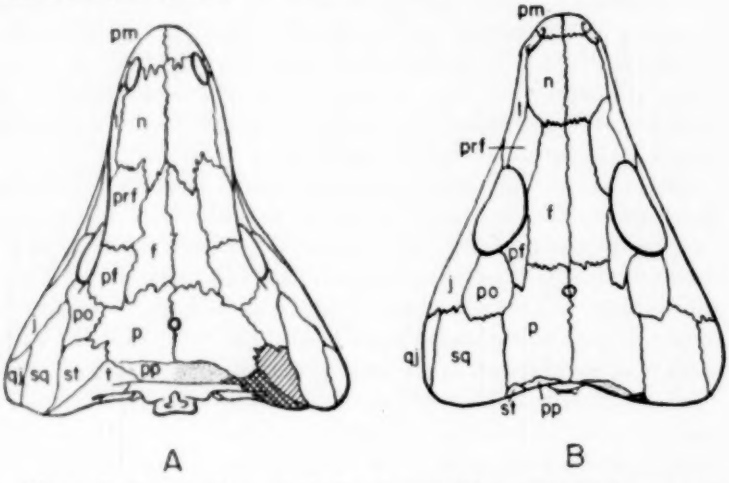

Figure 3. Dorsal views of skulls of captorhinomorph cotylosaurs: *A*, *Limnoscelis*, *B*, *Captorhinus*, to show contrast in skull pattern with that of microsaurs. Abbreviations and conventions as in figures 1 and 2; tabular cross-hatched.

posterior skull region. In microsaurs the otic notch has been obliterated—so thoroughly obliterated that dermal cheek and table elements are welded into a single unit. In early reptiles the notch is still retained in diadectomorphs; it is lost in captorhinomorphs, but welding of cheek and table is still imperfect, so that, as seen in *Limnoscelis* (and even in pelycosaurs) there persists a line of structural weakness between cheek and table components. The condition of supratemporal, tabular and postparietal is markedly different in the two groups. In reptiles in correlation with occipital shortening, the table exposure of both postparietal and tabular is much reduced and the supratemporal, never of great size, is reduced in parallel fashion. In microsaurs, the condition of these three elements differs greatly. The tabular is completely eliminated from the roof in every known instance, while in every form known except *Microbrachis* the postparietal remains well developed dorsally. The supratemporal is not reduced concomitantly with the posterior elements; instead, it is expanded to become a very prominent element in the pattern.

Using these diagnostic characters, it can be seen that certain forms often included in the microsaurs do not fall in this group, but are apparently proper reptiles, presumably cotylosaurs.

1. *Petrobates.* This name was applied by Credner to a small tetrapod from Niederhässlich which had earlier been confused by Geinitz and Deichmüller (1882, pp. 38-41) with "*Hylonomus*." Credner (1890, pp. 255-257) tabulates various differences between the two; and it is interesting that most of the features in which *Petrobates* differs from its contemporary are almost precisely those in which a primitive reptile might be expected to differ from a microsaurian amphibian (the skull structure is, unfortunately, poorly known). Both are small tetrapods with "holospondylous" vertebrae, but *Petrobates* is much the more stocky type, with stouter limbs and a shorter vertebral column (only about 19 presacrals as compared with a much higher number in "*Hylonomus*"); the manus is pentadactyl; haemal chevrons are present. A superficial but definitely diagnostic feature lies in the nature of the ventral squamation. Primitive reptiles as noted above are characterized by the presence of a system of V-shaped rows of slender oat-shaped or rod-shaped scales which contrast sharply with

the typical oblong amphibian scales of the microsaurs. Reptilian scales are present in *Petrobates*; "*Hylonomus*" has the microsaur type. It seems certain that *Petrobates* is a small reptile, very probably a captorhinomorph cotylosaur.

2. *Cephalerpeton*, a small tetrapod from the nodule beds of Mazon Creek, was described by Moodie as a microsaur. The specimen has been restudied by J. T. Gregory (1948a). On the basis of its structure, he argues that *Cephalerpeton* is a reptile and that hence microsaurs are reptiles. With his conclusion that *Cephalerpeton* is a reptile I am in complete agreement. But many of the features which he cites to prove its reptilian nature are crucial reptilian characters not found in typical microsaurs. The slender ventral abdominal ribs are typically reptilian and in contrast with microsaur scales. Presacral intercentra are present in the column in contrast to known microsaurs. The limbs are more highly developed than in microsaurs and in contrast to microsaurs in which the manus is known, the front foot is pentadactyl. In apparent contrast with microsaurs (but the evidence is poor) is the presence of a distinct coracoid ossification and of an entepicondylar foramen in the humerus. Significant is the reptilian nature of the ventral scales as elongate gastralia. The skull proportions, with a much abbreviate postorbital region, are those of a reptile and in sharp contrast to those of true microsaurs. It is unfortunate that the skull table is poorly preserved but it seems certain that the most diagnostic of all microsaur features—the large supratemporal—is absent from the skull pattern. Significant as well is the typical reptilian pterygoid flange described by Gregory, and the pronounced retroarticular process of the jaw. Altogether, *Cephalerpeton* appears to be a true reptile, quite unlike the typical microsaurs, and presumably a member of the captorhinomorph cotylosaurs (cf. *Romeria*). The only contradictory evidence is the fact that the neural arches do not appear to show the swollen condition normally found in cotylosaurs.

3. *Hylonomus*, type of the Microsauria of Dawson (although not of later writers), is known only from the erect trees of the Joggins—and very poorly known at that, for, as Steen (1934) points out, there is no guarantee that any of the material assigned to this genus properly belongs here apart from the type specimen and a second which is closely comparable. Both are very fragmentary and there is no skull

definitely associated. Even so, a variety of features indicate that we are dealing with a typical reptile. These include: (1) relatively large limbs; (2) caudal chevrons; (3) pelvis almost identical with that of such primitive reptiles as *Limnoscelis* (or even the pelycosaur *Ophiacodon*); (4) interclavicle of typical reptilian shape and especially (5) the scales, which are long slender rods of reptilian type and contrast strongly with those of the microsaurs of current concepts. *Hylonomus* is probably a captorhinomorph cotylosaur but might possibly be an ophiacodontoid pelycosaur.

Fritschia and *Leiocephalikon*, likewise from the Joggins, are equally poorly known (Steen, 1934, pp. 490-492), but the evidence suggests that they also are true reptiles.

The identification of *Hylonomus* as a true reptile leads to an embarrassing situation in nomenclature, for the term Microsauria was based upon this genus. If we were dealing with nomenclature on a generic or specific level, this would mean that the name Microsauria should follow its "type" and that some other term should be used for the forms discussed in this paper. But there is no "legal" compulsion upon one to do this; no advantage would be gained and, on the contrary, some confusion would result. I therefore propose to continue the use of the term Microsauria in its current sense, based upon *Microbrachis* and related forms.[8]

4. *Eusauropleura*. A specimen from the Linton Pennsylvanian sometimes considered a microsaur is that which forms the type of *Eusauropleura* (*Sauropleura*) *digitata* (Cope, 1875, p. 403, plate 37, fig. 1; Romer, 1930, pp. 135-136, fig. 26, etc.). The specimen exhibits the ventral side of the trunk of an animal, showing the ventral squamation, much of the limbs and ribs. The head is not preserved, the vertebrae are not visible and the hind leg is incomplete. Such data as can be obtained indicate that *Eusauropleura* is a true reptile: (1) the oat-shaped gastralia are of reptilian type, (2) the five-toed manus with a reptilian phalangeal formula of 2.3.4.5.3 is in contrast with the three-toed condition in known microsaurs, (3) the trunk was obviously relatively short and compact, after the primitive reptilian rather than the microsaurian pattern.

[8] I have profited from discussion with Dr. J. T. Gregory of this problem and others connected with the microsaurs.

MICROSAURS AS REPTILE RELATIVES?

Even if we can distinguish morphologically between microsaurs and forms definitely reptilian, may it not be that these forms can still be classed as reptiles in a broad sense or as forms ancestral to them? Many workers have claimed that the microsaurs are of reptilian nature, as, for example, Dawson (1863, p. 47, etc.), Baur (1897), J. T. Gregory (1948a), Huene (1948). But if the conclusions given in the last section are accepted, the arguments of the first three of the writers mentioned are, while perfectly acceptable, beside the present point, for they are based almost entirely on forms—*Hylonomus*, *Petrobates*, *Cephalerpeton*—which appear to be true reptiles and not microsaurs in the customary sense.[9] Huene's thesis rests in great measure upon certain features of rather doubtful or debatable nature, such as the presence of caudal chevrons, the identification as a tabular of the bone here called the supratemporal, presence of single occipital condyle, and of an otic notch.

[9] Baur's evidence for the reptilian nature of "*Hylonomus*" (of Niederhässlich) as well as *Petrobates*—two sacral ribs, for example—appears to rest on specimens identified by Credner as belonging to the latter genus.

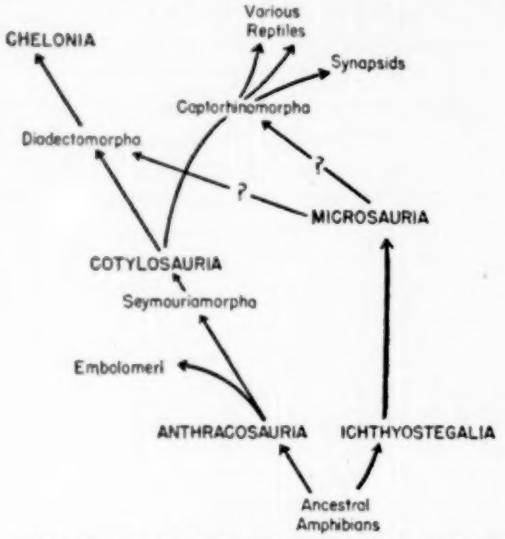

Figure 4. Phylogenetic diagram of possible origin of reptiles. Orthodox interpretation, through anthracosaurian labyrinthodonts, at the left; microsaurian derivation at the right.

Westoll (1942a, 1942b), from a somewhat different viewpoint maintains that the microsaurs, or adelospondyls, are ancestors of the captorhinomorph cotylosaurs. To properly evaluate his ideas it is necessary to view them in the light of currently accepted concepts of reptilian ancestry and phylogeny which have grown up through the work of Case, Williston, Watson and others (cf. fig. 4).

It is generally held that the reptilian pedigree stems from a point near the base of the Amphibia and leads through the anthracosaurian labyrinthodonts (these including the embolomeres) which had developed true centra and other reptile-like structures. *Seymouria* is a late representative of a group of anthracosaurs, or at least of forms of anthracosaurian derivation; it shows so many characters identical with those of reptiles as to be frequently included in the "stem reptiles" or, if not so included, is deemed ancestral to them. The reptilian basal stock is usually considered to form an ordinal group Cotylosauria. Known cotylosaurs, however, can be clearly divided into two groups, Diadectomorpha and Captorhinomorpha, as pointed out by Watson (1917) and emphasized by Olson (1947), who even argues that the two groups are so distinct that the term Cotylosauria should be abandoned. Both Olson and W. K. Gregory (1946) conclude that the turtles are descended from diadectomorphs and it is generally agreed that most, at least, of the other reptilian orders have sprung from the captorhinomorphs. Seymouriamorphs, diadectomorphs and captorhinomorphs differ in certain cranial structures, notably as regards the otic notch and adjacent elements, and the palate. *Seymouria* retains the primitive otic notch, diadectomorphs have a peculiarly exaggerated notch, captorhinomorphs have lost it; diadectomorphs have a specialized palate and dentition. In almost every other regard, however, the three groups are strikingly similar and many postcranial structures—even details of neural arch construction—are practically identical. It is difficult to escape the conclusion that the three are closely related, that the reptiles are monopryletic, and that their line of descent lies through the anthracosaurian labyrinthodonts.

Westoll's hypothesis is that the captorhinomorphs have descended from microsaurs (adelospondyls); that the seymouriamorphs are not phyletically related to reptiles; and

that while the seymouriamorphs are good anthracosaurs, both diadectomorphs and captorhinomorphs (via the microsaurs) have descended from the very ancient ichthyostegalians—very different amphibians indeed. Positive and convincing proof is required if one is to deny the seemingly certain relationship of *Seymouria* to the reptiles and establish a radically different line of reptilian ascent—proof which Westoll does not furnish. He cites the presence of certain microsaur-reptile similarities, attempts to bring limb structure of microsaurs in line with that of reptiles, and compares the captorhinomorph skull table structure with that of microsaurs. The presence of certain similarities between microsaurs and true reptiles is obvious; but these similarities are matched by still greater similarities between seymouriamorphs and reptiles and counterbalanced by differences which do not for the most part exist between reptiles and their presumed anthracosaur relatives. Limb comparisons force upon him the doubtful assumption that *Eusauropleura*, *Hylonomus*, and *Fritschia* are microsaurs related to *Microbrachis*. It is possible, perhaps, to evolve the skull pattern of reptiles from that of microsaurs, but it is a hard struggle. Captorhinomorphs exhibit the general reptilian trend toward a shortening of the skull table; microsaurs are persistently primitive and show absolutely no trend of this sort. In the captorhinomorphs, postparietal, tabular and supratemporal show concomitantly the expected reptilian drift in skull table structure—posterior movement and reduction in size. Not so in microsaurs, for while the tabular is eliminated in all known microsaurs, the supratemporal has expanded to unusual size and the postparietal generally resists reduction. I can think of no Paleozoic amphibian forms (except for some of the eel-like lepospondyls) which, on the basis of skull table structure, are more unlikely reptile ancestors than the microsaurs. It is true that captorhinomorphs and microsaurs have in common one advanced feature in this region of the skull—elimination of the otic notch. However, this creates more difficulties than it solves; for, unless reptiles are (most improbably) polyphyletic, it involves development of the diadectomorph notch in secondary fashion. I have tried (1946) to explain how this might have happened; but my attempted explanation has not, I think, been satisfactory to my colleagues (nor, indeed to myself).

THE PHYLOGENETIC POSITION OF MICROSAURS

As to the ancestry of the Microsauria, descent from the ancient ichthyostegids is not unreasonable. Westoll (1942b) has advocated this pedigree, and I had independently reached the same conclusion. The evidence is, of course, incomplete and based essentially on the skull roof pattern and proportions. The postcranial skeleton of ancestral ichthyostegids has not been described. It is highly improbable that they had "holospondylous" vertebrae, but this is no bar to microsaur derivation, for it is obvious that vertebrae of this sort have arisen more than once among amphibian groups.[10]

In the discussion above, our attention has been concentrated on "typical" microsaurs. The question of the relationships to them of various specialized holospondylous types of the Paleozoic—the *Lysorophus*, *Ophiderpeton* and *Dolichosoma* groups, particularly—is worthy of further study, although it is probable that firm conclusions must await the discovery of new materials.

If reptilian relationship be denied, are the microsaurs terminal members of their line, or are they, in some sense or other, to be considered as ancestral to any later amphibians? As noted earlier, *Lysorophus*, a member of the microsaurian "periphery," is a possible ancestor of the Apoda. This form is often considered to be an ancestral urodele. It is, one would think, too far gone in body elongation and limb reduction to be seriously thought of in this light. But may not some other microsaur have to be the urodele ancestor? In most regards the "typical" Microsauria are reasonable urodele ancestors. The one strong objection lies in the palatal structure. The urodele palate was unquestionably formed by modification from a primitive amphibian type, with small interpterygoid vacuities and a movable articulation with the braincase. But one would expect late Carboniferous or early Permian ancestors of the urodeles to exhibit a trend in the modern direction (such as is shown in contemporary labyrinthodonts and even *Lysorophus*). The typical Microsauria show no such trend; on the contrary they are persistently primitive in this regard.

[10] Note that even among the stereospondyls the brachyopids have evolved a "holospondylous" centrum by elaboration of the intercentrum.

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STANDARDS FOR GRADING TEXTURE OF EROSIONAL TOPOGRAPHY

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ABSTRACT. A study of texture, or drainage density, of stream-eroded topography was made to derive a ratio which will grade the texture on contour topographic maps and to establish limiting values of this ratio for "coarse," "medium," and "fine" texture. Standard values are suggested for the three texture grades, based on the application of the derived texture ratio to type areas. The term "ultra-fine texture" is used to designate the extremely fine dissection of badland topography. A comparative study shows that the texture ratio is a logarithmic function of R. E. Horton's "drainage density." It is hoped that these standards will prove of value in later quantitative geomorphic studies in which causative factors are being related to land forms.

INTRODUCTION

"TEXTURE of topography" was defined by Douglas Johnson (1933) as the "average size of the units composing a given topography." The term is here restricted to the description of regions dissected by streams, and is an expression of the spacing of the smallest drainage lines, both intermittent and perennial, whether or not these are represented on the map by symbols. It is therefore essentially synonymous with "stream frequency" (Horton, 1945), measured in terms of the number of stream channels per unit area.

Following a quantitative approach to geomorphology, a study of topographic texture, or drainage density (defined hereafter), was undertaken with the objective of deriving a ratio to grade the texture on contour topographic maps and of establishing limiting values of this ratio for "coarse," "medium," and "fine" textured topography. Standard United States Geological Survey topographic maps, on the scale of 1/24,000, were used for the study. Only recent maps of large scale can be relied upon to indicate all significant stream channels, both perennial and intermittent. In the present study, where data are taken from maps, emphasis must be placed on the necessity of using recent and accurate maps of the largest scale available.

The texture of topography depends upon a number of variable factors which may be divided into two classes: natural factors and map factors. Of the natural factors the most im-

portant are climate, vegetation, rock or soil type, rainfall intensity, infiltration capacity, relief, and stage of development. In general, weak rocks, unprotected by vegetation, produce fine texture; massive, resistant rocks cause coarse texture. Sparse vegetation of arid climates causes finer textures than those developed on similar rocks in a humid climate. Textures tend to be coarse in the initial and early stage of the erosion cycle; finest in early maturity when relief is greatest. Map factors affecting texture include the scale of the map and the accuracy of the mapping.

STREAM FREQUENCY AND DRAINAGE DENSITY

Two ratios which have been used to express the texture of topography are "stream frequency" and "drainage density," derived by R. E. Horton (1945).

"Stream frequency" is defined as the number of streams per unit area in a given drainage basin and may be expressed by the equation $F_s = N/A$, in which F_s represents stream frequency, and N equals the total number of streams in a drainage basin of A areal units.

"Drainage density" is defined as the length of streams per unit area in a given drainage basin and may be expressed by the equation $D_d = \Sigma L/A$ in which ΣL represents the total length of streams and A represents the area, both in units of the same system.

The term "texture" has been used in much the same sense as both "drainage density" and "stream frequency." However, values of drainage density and stream frequency for small and large drainage basins are not directly comparable because they usually vary with the size of the drainage area. A large drainage basin may contain as many small, or fingertip, tributaries per unit area as a small drainage basin, and in addition it usually contains a larger stream or streams. This effect may be masked by the increase of drainage density and stream frequency in the more rugged headward parts of the drainage basins.

DERIVATION OF THE TEXTURE RATIO

Testing of several possible texture ratios resulted in selection of the ratio of the number of crenulations on that contour having the maximum number within the drainage basin to the length of the perimeter of the basin. Each sharp outward bend in the contour is considered to represent a stream channel and

therefore to reflect the actual spacing of the drainage lines even though they are not shown on the map as individual streams.

This texture ratio is expressed by the equation T=N/P, where T represents the texture, N is the number of crenulations on the selected contour, and P is the length of the perimeter of the basin given in miles or fractions thereof.

Figure 1 illustrates the method of applying the equation. The hachured contour is the contour having the maximum number of crenulations. This contour commonly cuts the perimeter of the basin on opposite sides at points in the lower half of the basin. The dotted line indicates the perimeter of the basin traced around the divide. Length of perimeter may be measured with a chartometer.

DESCRIPTION OF LOCALITIES

Two general areas were selected for testing the texture ratio; one in southern California, the other in north-central Pennsylvania. Selection was made on the basis of the appear-

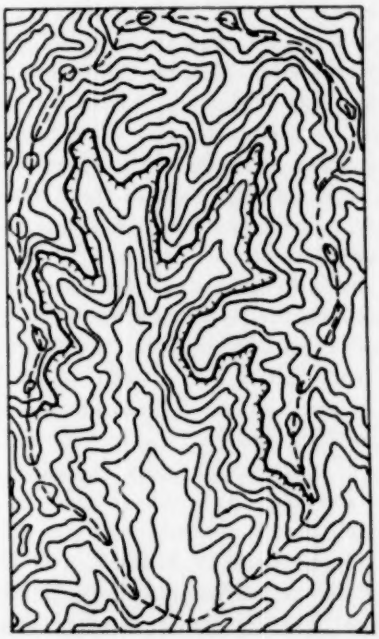


Figure 1. On the drainage basin outlined by dashed line the contour having the maximum number of crenulations is shown by hachures.

ance of fineness of dissection as observed on the topographic maps.

The California region was chosen as a possible type area for the grades of texture judged to be illustrations of medium and fine grades. Portions of four United States Geological Survey quadrangles, on a scale of 1/24,000, were used: Sunland, Altadena, La Crescenta, and Little Tujunga. The climate in this region is of the Mediterranean type with major rainfall in the winter and with very dry summers. Vegetation is a sparse chaparral which affords only moderate protection to the surface. The geology of the area is quite complex, but within small areas used here there is a similarity of land forms and drainage basins. One area, confined to the Verdugo Hills and including portions of the Altadena, Sunland, and La Crescenta quadrangles, is underlain by the Wilson diorite and the San Gabriel meta-sediments. That part of the Little Tujunga quadrangle in the vicinity of Kagel Canyon, which was used as representing fine texture is underlain by weak Pleistocene sediments, the Temescal and Victor formations.

The Pennsylvania locality was selected as a possible type area for coarse-textured topography. Three United States Geological Survey quadrangles, on the scale of 1/24,000, were used: Driftwood, Sinnemahoning, and Cameron. The climate here is a humid continental type with fairly uniform precipitation distribution and a coniferous-deciduous forest cover. The underlying strata of this part of the Appalachian Plateau are approximately horizontal and consist largely of resistant coarse-grained sandstones.

The size of the individual drainage basins varied greatly in the two regions. In the California areas the lengths of basin perimeters varied from 0.59 miles to 2.48 miles; in the Pennsylvania area from 2.3 miles to 6.61 miles in length. The basins were, however, similar in that the master streams are of the second or third orders (Horton, 1945, p. 281). Thus the samples are of comparable units of drainage networks.

The intricate dissection and strong relief in the California localities were such that it was necessary to enlarge the maps photostatically to the scale of 1/6000 in order to make accurate counts of the contour crenulations. Study of the Pennsylvania area was, however, made directly from the original maps.

VALUES OF THE TEXTURE RATIO

The texture ratio was obtained from forty-five small drainage basins; thirty in California and fifteen in Pennsylvania

TABLE 1

Texture ratio data for the Pennsylvania and California localities.

	P (*miles*)	N	N/P	Area (*sq. mi.*)	ΣL (*miles*)	ΣL/A
Driftwood, Pa.	2.90	7	2.41	.516	3.25	6.30
	3.61	9	2.49	.599	2.91	4.86
	2.90	7	2.41	.483	2.00	4.14
Sinnemahoning, Pa.	5.20	17	3.25	1.670	6.59	3.94
	6.61	21	3.17	2.336	8.45	3.65
	3.90	9	2.30	.783	2.84	3.63
	2.30	7	3.04	.373	2.20	5.88
	3.00	12	4.00	.577	3.33	5.76
Cameron, Pa.	2.30	6	2.60	.347	1.17	3.37
	3.90	8	2.05	.757	2.24	2.95
	5.43	8	1.47	1.063	4.05	3.81
	3.40	4	1.17	.605	2.19	3.62
	3.70	11	2.97	.721	3.42	4.73
	3.29	7	2.12	.577	2.42	4.18
	3.98	11	2.78	.742	2.65	3.58
Sunland, Calif.	.89	10	11.22	.049	1.70	34.50
	.96	8	8.33	.050	.85	17.00
	1.36	15	11.03	.118	2.28	19.20
	1.29	11	8.52	.088	1.77	22.10
	1.53	10	6.53	.119	2.01	16.90
	1.01	9	8.91	.056	1.18	21.10
	.75	5	6.61	.027	.53	19.70
	.81	8	9.87	.032	.93	29.30
Altadena, Calif.	1.38	12	8.70	0.80	1.34	16.70
	1.54	21	13.63	.128	2.30	17.80
	1.62	17	10.49	.181	2.74	15.20
	1.05	7	6.66	.060	.98	16.40
	.95	4	4.21	.050	.85	17.10
	1.18	10	8.47	.086	1.40	16.30
	1.31	13	9.92	.094	1.47	15.60
	.83	7	8.43	.045	.68	15.20
	1.07	9	8.41	.056	.93	16.70
La Crescenta, Calif.	1.33	7	5.26	.079	1.50	18.90
	2.02	14	6.93	.205	4.12	20.20
	2.08	19	9.13	.244	4.10	16.80
	2.48	21	8.46	.319	5.53	17.40
	1.66	9	5.42	.139	2.22	16.00
	1.05	8	7.61	.063	1.19	18.90
Little Tujunga, Calif.	1.30	31	23.84	.096	3.13	32.60
	.75	17	22.72	.032	1.17	36.60
	.88	14	15.90	.044	1.37	31.10
	1.02	11	10.78	.052	1.38	26.60
	.69	13	18.84	.023	.76	34.00
	.59	6	10.16	.014	.50	35.90
	.75	9	12.32	.032	.90	28.10

(table 1). Values for N/P in the California localities varied from a low of 4.2, for one drainage basin in the Altadena quadrangle, to a high of 23.8 for one basin in the Little Tujunga quadrangle. For the region in north-central Pennsylvania values for N/P varied from a low of 1.1 for one basin in the Cameron quadrangle to a high of 4.0 for one basin in the Sinnemahoning quadrangle.

In addition to determining the texture ratios of individual drainage basins it is necessary to establish a mean value for N/P which will describe the texture of each area as a whole. The size of individual drainage basins must be taken into consideration when determining the mean value of the texture ratio, because the same weight cannot be attached to the texture ratio of a small drainage basin as to a large one. The weighted mean value for the topographic texture in a given region may be taken as the ratio of the sum of the products of the basin area times the texture ratio for each basin to the sum of the areas of the basins. This may be expressed by the equation $T_m = \Sigma(AN/P)/\Sigma A$, in which Σ represents the sum, A represents the area for each individual drainage basin, and N/P is the texture ratio for each basin as previously defined. In this manner final values for T_m are weighted according to size of the various drainage basins included.

Table 2 gives values of T_m for the seven quadrangles studied, listed in the order of increasing magnitude and calculated from the data of table 1. Mean values did not approach the lowest value for N/P of 1.1 for one basin in the Cameron quadrangle, nor did they approach the highest value obtained in the Little Tujunga quadrangle for N/P of 23.8. The results are believed consistent enough within each area to be used in establishing standards for grading topographic textures.

TABLE 2

Mean values of the texture ratio for the Pennsylvania and California localities.

	ΣA (*sq. mi.*)	$\Sigma(AN/P)$	T_m
Cameron, Pa.	4.812	10.151	2.10
Driftwood, Pa.	1.598	3.899	2.43
Sinnemahoning Pa.	5.739	18.075	3.14
La Crescenta, Calif.	1.049	7.996	7.62
Sunland, Calif.	.539	5.087	9.43
Altadena, Calif.	.780	7.460	9.56
Little Tujunga, Calif.	.293	5.245	17.83

PROPOSED STANDARDS FOR GRADING TOPOGRAPHIC TEXTURE

Based on values of T_m the following standards for grading the classes of topographic texture are proposed: For coarse-textured topography, T_m is below 4.0. A medium-textured topography may have a value ranging from 4.0 to 10.0. A fine-textured topography will have a value above 10.0.

These standards would place the Appalachian Plateau area of resistant sedimentary strata in the coarse-textured division. Of the California localities, those in the Verdugo Hills on Wilson diorite and San Gabriel meta-sediments would be classified as medium-textured, while the Little Tujunga locality, underlain by very weak Pleistocene sediments, would be classified as fine-textured.

ILLUSTRATIONS OF THE THREE TEXTURE GRADES

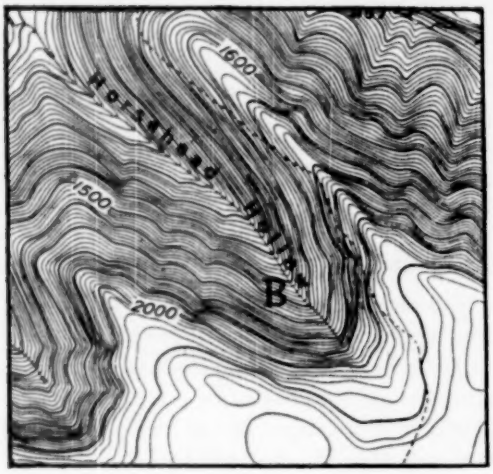
Maps have been prepared to demonstrate the appearance of basins having the three texture grades proposed in this paper (figs. 2, 3, 4). Each map shows one square mile for a visual comparison of the textures.

The first illustration, figure 2-A, shows a small drainage basin, Horsehead Hollow, in the Driftwood, Pennsylvania, quadrangle. This is a region of coarse-textured topography; the value N/P for this basin is 2.4. The mean value for the texture ratio of the area is also 2.4. The basin has only one main stream with two or three possible intermittent tributaries. A drainage map of this area, figure 2-B, in which the contours have been omitted, shows the scarcity of channels in an area of coarse texture.

An illustration of medium-textured topography is taken from the La Crescenta, California, quadrangle, in the vicinity of Cunningham Canyon. (fig. 3-A). The value of N/P for the basin drained by Cunningham Canyon is 5.4, whereas the mean value for the texture in the Verdugo Hills on this quadrangle is 7.6. Figure 3-B, showing the possible stream channels as indicated by the contour crenulations, illustrates the increase of drainage density corresponding to the increase of the texture ratio.

The southwest portion of the Little Tujunga, California, quadrangle, in the vicinity of Kagel Canyon, is a very good example of fine-textured topography (fig. 4-A). The main basin shown, which drains to the south, has a value of N/P

=23.8. The mean texture ratio in this portion of the quadrangle is 17.8. The drainage map (fig. 4-B) shows that the region has a much higher drainage density than the medium-textured area.



A.

B.

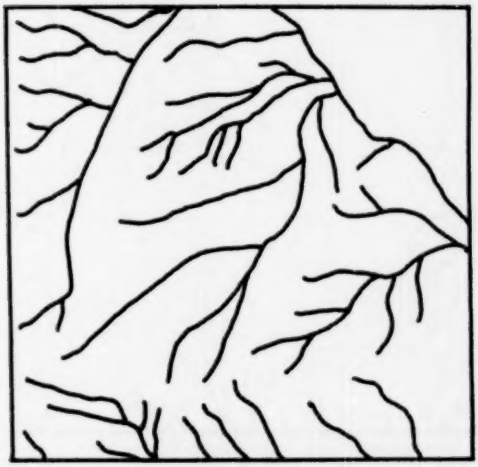
Figure 2. Coarse texture. A. Topographic map. B. Drainage map.

Figure 5 shows medium-and coarse-textured areas on two common scales: 1/31,680 and 1/63,360. These can be used for comparison with standard United States Geological Survey topographic maps.

ULTRA-FINE TEXTURES

The extremely fine textures of badlands on weak clays or

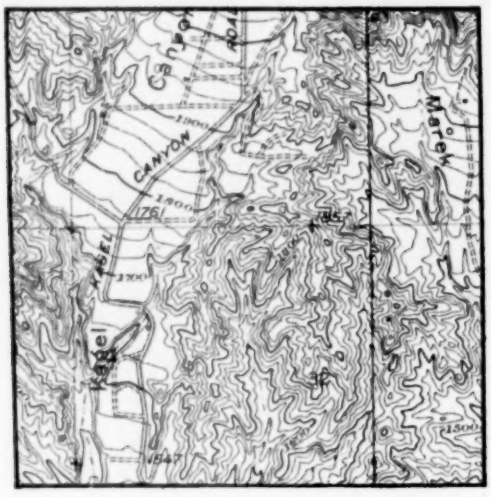
A.



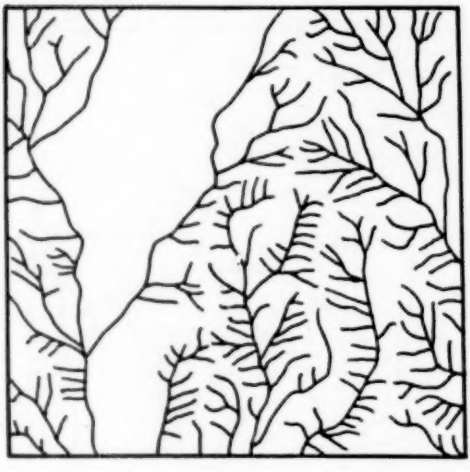
B.

Figure 3. Medium texture. A. Topographic map. B. Drainage map.

marls cannot be adequately shown on the topographic maps of the scale 1/24,000 or smaller. Nevertheless these types are a part of the texture-drainage density series and must be analyzed, even though special maps must be made on an appropriately large scale. The term "ultra-fine texture" is here ap-



A.

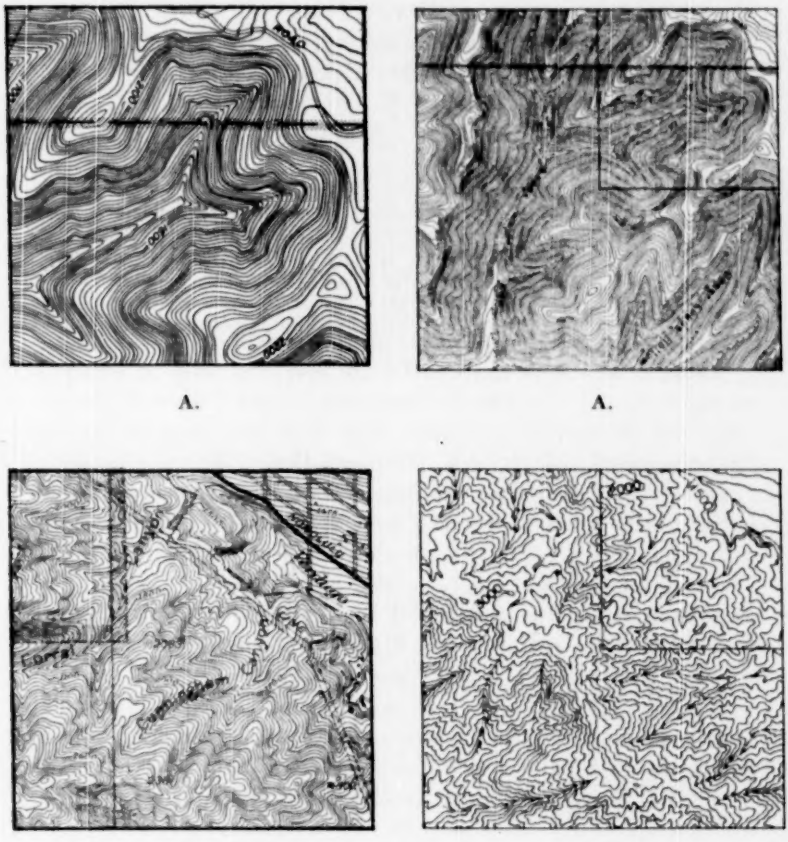


B.

Figure 4. Fine texture. A. Topographic map. B. Drainage map.

plied to such badlands. The texture ratio was measured in two bandland areas; one a dissected clay-sand back-fill near Perth Amboy, New Jersey, the other in the Petrified Forest, Arizona.

In the Perth Amboy locality six small basins were measured from a special topographic map prepared in 1948 by Professor A. N. Strahler and Mr. Donald R. Coates, of Columbia University, as part of a project to study the erosional development of badland topography. The scale of the map is 1/120; the contour interval is one foot.



A. A.

B. B.

Figure 5. Illustrations of coarse and medium-textured topography at two common scales. A. Coarse texture, 1/31,680 and 1/63,360. B. Medium texture, 1/31,680 and 1/63,360.

This unusual area has an intricate drainage network developed on a homogeneous mixture of sand and clay, which has an extremely low resistivity to erosion and a low infiltration capacity. Although the area is in a region having a humid-temperate climate, there is no vegetation. Texture ratios for the six basins measured vary considerably, but are all greater than 100. The values may be compared from table 3, the lowest value of N/P being of the order of 139; the highest 278.

TABLE 3

Texture ratio data for the Perth Amboy, N. J., and Petrified Forest, Arizona, localities.

	P (*miles*)	N	N/P	Area (*sq. mi*)	ΣL (*miles*)	ΣL/A
Perth Amboy, N. J.	.0216	3	139	.0000195	.0118	605
	.0180	5	278	.0000160	.0130	810
	.0204	4	196	.0000190	.0160	842
	.0236	6	254	.0000258	.0218	845
	.0184	4	218	.0000195	.0133	680
	.0163	4	246	.0000184	.0125	675
Petrified Forest, Arizona	.160	19	119	.00125	.338	270
	.149	19	127	.00109	.274	254
	.104	11	106	.0053	.134	253

Three basins were measured from a special map of badland topography on the Chinle formation in the Petrified Forest National Monument, Arizona. This area was mapped during the summer of 1949 by Mr. Brainerd Mears, Jr., of Columbia University. The scale of the map is 1/480; the contour interval five feet. The region has a semi-arid climate in which summer rains are sporadic and torrential. The weak nature of the Chinle formation and the lack of a vegetal cover result in the formation of a finely-dissected badland topography. Values for the texture ratio in the three basins measured were all slightly greater than 100, as shown in table 3.

These results indicate that the texture ratio for badlands can greatly exceed the values established in this paper for fine-textured topography. However, when the usual United States Geological Survey or Army Map Service topographic map is used, with a scale of 1/24,000 or smaller, any area having a texture ratio greater than 10.0 will appear as finely dissected as the limitations of the map scale will permit. Increasing drainage densities are not further differentiated beyond this point by the contour map.

The term "ultra-fine texture" may be applied to areas having a texture ratio greater than 50. Texture ratios of this magnitude are adequately shown only on large scale and detailed maps such as those of the Perth Amboy clay topography and the Chinle badlands.

RELATION OF TEXTURE RATIO TO DRAINAGE DENSITY

A comparative study has been made of the relation between the texture ratio (T=N/P) and Horton's drainage density ratio (D_d=ΣL/A). In order to establish this relationship, drainage lines were drawn into each channel indicated by the contours so that the total lengths could be measured. Using these data it was possible to determine the drainage density for the fifty-four basins for which the texture ratio had been determined.

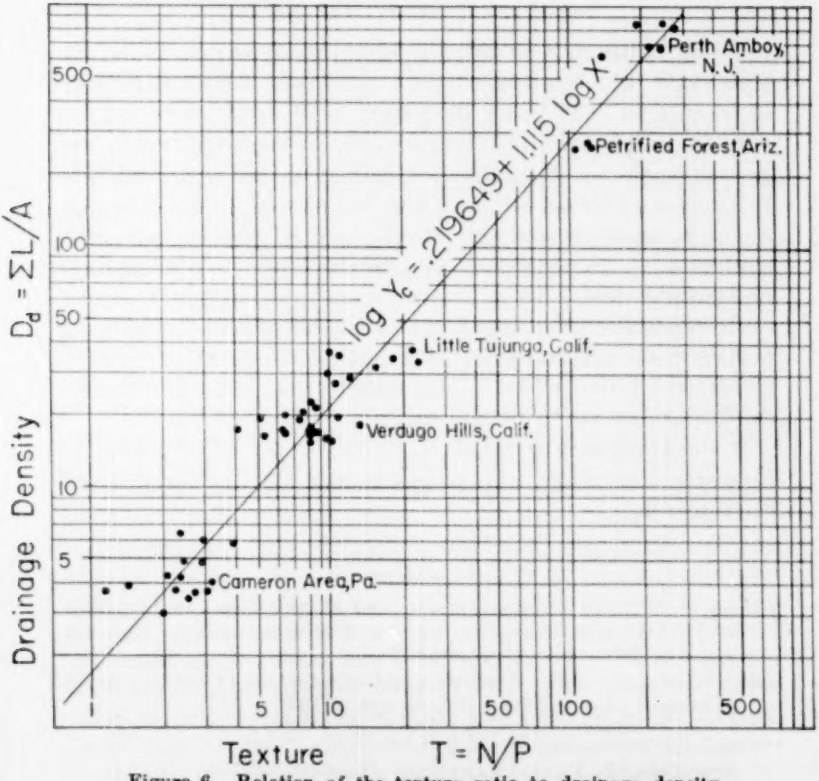


Figure 6. Relation of the texture ratio to drainage density.

The data were then plotted on log-log paper; the values for drainage density as ordinates, texture ratios as abscissas (fig. 6). The points formed a scatter zone approximating a straight line, indicating that the drainage density is a logarithmic function of the texture ratio. An estimating equation was then derived using the general form:

$$\log Y_c = \log a + b \log X$$

which is the logarithmic form of:

$$Y_c = a X^b.$$

By the method of least squares the following constants were derived:

$$\log a = .219649$$

$$b = 1.115$$

Substituting these values in the general equation we have:

$$\log Y_c = .219649 + 1.115 \log X.$$

Using figure 6, it is possible to translate any value of texture ratio into the approximate equivalent drainage density, or vice versa. The latter procedure is of value when one has only an air photograph, from which only drainage density can be measured and the equivalent texture grade is desired. The high degree of correlation in the two sets of values serves as a check upon the over-all consistency of the texture ratio method as a simple means of grading texture from contour topographic maps.

In conclusion it is hoped that these standards for grading texture from contour topographic maps will prove of value in later quantitative geomorphic studies in which causative factors are being related to land forms.

Acknowledgment is made to Professor A. N. Strahler, of Columbia University, who suggested the study and supervised the research.

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Columbia University,
New York, N. Y.

COMMUNICATION

NEW JOURNAL OF INTEREST TO GEOLOGISTS

A new geochemical journal, GEOCHEMICA ET COSMOCHIMICA ACTA, is being published by Butterworth-Springer, 436 Strand, London, W. C. 2, England, under the editorship of Professor L. R. Wager. The journal is international in scope and the plan is to give prompt publication to geochemical papers from all over the world. They will be published in English, French or German, with English summaries. Authors are to be given 75 reprints free of charge. Manuscripts should be sent to Earl Ingerson, U. S. Geological Survey, Washington 25, D. C., who is American editor for the new publication.

Subscription prices have not yet been announced, but the American agent is the Academic Press, Inc., 125 East 23rd Street, New York 10, New York, to whom inquiries should be addressed.

REVIEWS

The Geology of the Bergamasc Alps, Lombardia, Italy; by L. U. DE SITTER and C. M. DE SITTER-KOOMANS. 257 pp., 38 text figs., 43 plates. Overdruk uit Leidse Geologische Mededelingen, Deel XIV-B, 1949.—This substantial contribution to knowledge of geology in the southern part of the Alps is the result of summer field studies, in the years 1926 to 1939, by staff members and advanced students of Leyden University. The area mapped in detail has a maximum length of about 52 miles, extending from Lake Como on the west to the Oglio River on the east; it varies in width from 12 to 25 miles, the northern boundary lying near parallel of latitude 46° 05′. Bedrock geology of this area is depicted on two attractive sheets, in colors, to the scale 1:50,000, with topographic contours spaced at 100 meters. Two additional sheets, also in color, show to the same scale 27 structure sections, all extending north-south, essentially at right angles to the structural grain. Four additional folded plates, drawn to smaller scales, show (1) igneous bodies of the Bergamasc Alps; (2) major tectonic features of the area, by line symbols and by generalized structure contours; (3) tectonic features of a much larger area, the entire Lombardic Alps; and (4) variations in thickness and facies of the sedimentary formations, in a generalized west-east section from the Lugano region to South Tyrol.

The textual treatment is divided into three principal sections. Part I deals with the petrography of metamorphic and igneous rocks, and includes numerous chemical analyses. These rocks con-

sist of: (1) the "basement series" of ortho- and paragneisses, injection gneiss, phyllite, amphibolite, and other metamorphic types, all cut by bodies of granitic rocks, chiefly granodiorite, believed to be of late Carboniferous (Asturian) age; (2) Permian volcanic rocks; (3) Triassic and Tertiary intrusive bodies.

Part II describes the sedimentary formations which, exclusive of Pleistocene and Recent deposits, range in age from Permian through the three Mesozoic periods. The total thickness of pre-Cretaceous systems reaches a maximum of more than 20,000 feet in the central part of the area. There are striking similarities, at a number of horizons, to sections displayed in the East Alpine thrust sheets of Austria. This part of the monograph presents much information of value to students of lithofacies, and also to biostratigraphers.

Part III describes the structure and outlines the tectonic development of the Bergamasc mountain unit. In this division of the Alps the thrusting and overfolding are directed in the main toward the south, in contrast to the northward-reaching nappes of Switzerland. The Insubrian Line, marking a sharp boundary between the two unlike structural provinces, extends nearly east-west some miles north of the Bergamasc Alps. Directly north of the line the thrust sheets of the Central Alps are essentially vertical; this is the "root zone" of the Pennine nappes. South of the line is the Orobic belt of basement rocks, which has been thrust southward to form the highest structural "tread" of the Lombardic Alps. Other thrusts and related folds, affecting the sedimentary section, complete a series of broad steps descending to the Po River plain. The structure is locally complex, but as a whole is much simpler than that of the Swiss Alps. From the Insubrian Line southward the deformation represents the later (post-Oligocene) Tertiary episodes of Alpine orogeny.

We are indebted to our Dutch colleagues for a clear presentation of their results in English. Although numerous words are misspelled, there is no difficulty in following the exposition. How many geologists of the English-speaking world could so successfully write a similar monograph in Dutch, or in any other language of the European continent? CHESTER R. LONGWELL

Allgemeine Botanik—Ein Lehrbuch auf vergleichend-biologischer Grundlage; by WILHELM TROLL. Pp. xv, 749. Stuttgart, Germany, 1948 (Ferdinand Enke Verlag, DM 56.00, 60.00 bound).—This new and voluminous text is an original attempt to provide a much needed modern treatment of general botany covering a considerable diversity of subjects, namely morphology, anatomy (including cytology and histology), physiology (including nutrition, respira-

tion, water relationships, morphogenesis and tropisms), and reproduction, but excluding genetics. As a fundamental text the book is significantly unorthodox and differs from other older standard works both in the selection and the arrangement of its subject matter.

Morphology and discussions of morphological principles form the backbone of the book, but some aspects of physiology are also very adequately treated and numerous biochemical data not usually given in this kind of general text have been included. Theoretical considerations manifest a good understanding of the evocator-reaction system concept and of the plant as a self-regulatory entity. In addition, useful parallels are drawn between plants and animals. Some aspects of growth and differentiation, now prominent in contemporary research, have been treated relatively briefly or are omitted, such as growth-relationships, meristems, synthetic growth substances, and the concepts of reactivity, potency and determination.

Led by holistic-morphological principles, the author has abandoned in his text to a considerable degree the customary segregation of physiological and morphological topics. Thus osmosis, turgor, etc., are treated under the heading of cytology while some anatomical and morphological features appear in the physiological sections. The ensuing diffusion of the subject matter is, however, somewhat counteracted by good cross-reference from one chapter to another. Didactically this may be subject to some criticism, as may the introduction of certain terms, such as Ueberpflanzen (superplants) for epiphytes, which seem unnecessary and impractical. These, however, are minor considerations affecting little the usefulness of this interesting book which contains a profusion of good illustrations. More serious is the omission of citations, a bibliography, and an author's index. ROBERT BLOCH

Giant Brains or Machines That Think; by EDMUND C. BERKELEY. Pp. xvi, 270. New York, 1949 (John Wiley & Sons, Inc., $4.00).—Complex machinery for handling information and computing is, every day, attaining a position of greater importance in modern technology. In this provocative volume Mr. Berkeley describes the mechanical structure and operation of some of these machines and attempts to evaluate their present and future significance to society. The author, who has a wide background of experience in the field of automatic computing machinery, is well qualified for the task he has undertaken.

Giant Brains begins with a discussion of the sense in which machines may be said to be capable of thinking. It illustrates some of the types of mechanical thought with reference to a specific simple

mechanical brain, which the author calls Simon after a distinguished predecessor. Simon, however, is not as simple as the reader may at first hope. If actually constructed, he would require approximately fifty relays connected in a very formidable electrical network.

Punched-card calculating techniques, which play an important role in many modern mathematical computers and which are used, as well, in business and accounting, are treated in detail. Separate chapters are reserved for discussions of the components, capabilities and operational procedures of four representative calculators in use at the present time. These are the Massachusetts Institute of Technology's Differential Analyzer No. 2, the IBM Automatic Sequence-Controlled Calculator at Harvard, the ENIAC (Electronic Numerical Integrator and Calculator) developed at the University of Pennsylvania, and the Bell Laboratories' General Purpose Relay Calculator.

A recent machine of a different sort, the Kalin-Burkhart Logical Truth Calculator, which solves problems in Boolean algebra (the algebra of logic), is explained. This fascinating computer promises to be useful in drafting complex contracts and in checking them for freedom from "loop holes" and logical contradictions.

Mr. Berkeley, in the final chapters, discusses the Giant Brains of the future and the dangers which they may present to society. He concludes that the chief perils are the physical harm which robot-controlled weapons can inflict and the unemployment which combinations of thinking and acting machines may produce by usurping the functions of men. The real and immediate necessity for serious thought on these problems is forcefully argued.

The author is careful to explain in the preface that the book has been written with the use of a minimum of technical terms and concepts. It is, he says, intended for everyone. Unfortunately, this quest for universal appeal and understanding makes the work, in many instances, superficial. The reader's interest is often aroused to a high peak by a provocative statement; but the subsequent explanation is frequently so shallow as to leave him rather unsatisfied.

A very valuable bibliography of more than 250 references on calculators and related topics is included in *Giant Brains*. This would serve as an excellent starting point for a deeper investigation of the field.

FRANKLIN C. BROOKS

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